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Cities and the Triple Bottom Line

The Causal Effect of Socio-Economic Sustainability on Environmental Sustainability

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Abstract

Cities are experiencing substantial population growth, they generate about 80 percent of global GDP and they are in power of local legislation. This makes them crucial actors in facing sustainability challenges. A framework that allows for a holistic approach to sustainability is the triple bottom line, which advocates for joint consideration of social, economic, and environmental development. In practice, these three dimensions are mostly considered separately without paying attention to causal relationships among each other. However, understanding these causalities is necessary for designing effective sustainability strategies and accurately assessing city sustainability. This study provides evidence for the causal effects of social and economic sustainability on environmental sustainability. To avoid simultaneity bias, this study applies a shock-based instrumental variable approach, which isolates the causal effect of socio-economic on environmental sustainability from the causal effect in the reverse direction. The study sample encompasses 60 German cities, for which data was collected for 30 indicators between the years 2000 and 2013. The chosen shock is the financial crisis of 2007, as it has strongly and directly affected socio-economic indicators, but not environmental indicators. The empirical analysis of the data confirms the presence of causality from social on environmental sustainability, as well as from economic on environmental sustainability. This implies that changes in one socio-economic sustainability do not translate into equivalent changes in overall sustainability, but are accompanied with further changes, that need to be considered.

Keywords: city sustainability, triple bottom line, strong sustainability, shock-based instrumental variables, Doughnut economics

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List of Abbreviations

2SLS	Two-stage least-squares
BBSR	Federal Institute for Research on Building, Urban Affairs and Spatial Development of Germany
EU	European Union
GDP	Gross domestic product
ICTs	Information and communication technologies
IV	Instrumental variable
NO2	Nitrogen dioxide
OLS	Ordinary least squares
PM10	Particulate matter (<10 μm)
RD	Regression discontinuity
SA	Sustainability assessment
TBL	Triple bottom line

1 Introduction

Sustainability has become a dominating topic in many dimensions. In recent years, scientific research has gained importance, which can be seen from the surge in academic publications on sustainability-related topics (Purvis, Mao & Robinson, 2019). At the same time, businesses aim to find sustainable innovations (Mio, Panfilo & Blundo, 2020), while a large share of individuals strives for more sustainable consumption (Trudel, 2019). Governments act as a policy forum, they provide education for sustainability, they create platforms for concrete actions for more sustainability (Wang, Van Wart & Lebredo, 2014), and many of them adopt sustainability practices (Sodiq, Baloch, Khan, Sezer, Mahmoud, Jama & Abdelaal, 2019). While national governments are certainly important actors in dealing with sustainability issues, local governments, such as city governments, are at least equally important (Wang, Van Wart & Lebredo, 2014). Since 2009, urban environments are home to more than half of the global population and this share is expected to reach 70 percent by 2050 (Raworth, 2017). Furthermore, about 80 percent of global GDP is generated in cities (UN-Habitat, 2022). At the same time, negative externalities make cities a serious threat to environmental conservation (Mori & Christodoulou, 2012). All of this turns cities into important actors in taking environmental responsibilities seriously, supporting their citizens, and ensuring the reliable functioning of the economy that brings prosperity to the society. To achieve global sustainable development, sustainable urban environments (or cities – hereafter, the terms are used interchangeably) are substantial and to achieve sustainable cities, we must study and understand them better.

1.1 Research Problem

Large numbers of studies concerning various aspects of sustainability at the city level have been and are still being conducted. The multitude of different concepts and methods that are being applied makes it a highly heterogeneous field (Fu & Zhang, 2017; Kaur & Garg, 2019; Shmelev & Shmeleva, 2019). Despite the numerous and diverging perspectives on city sustainability, scholars often agree on three dimensions that should be considered. Those dimensions are environmental, social, and economic sustainability (Ahvenniemi, Huovila, Pinto-Seppä & Airaksinen, 2017; Cohen, 2017; Kawakubo, Murakami, Ikaga & Asami, 2018; Li & Yi, 2020; Mori & Yamashita, 2015; Yigitcanlar, Kamruzzaman, Foth, Sabatini-Marques, da Costa & Ioppolo, 2019). This three-pillar design is also known as the triple bottom line (TBL). Its most important message is that sustainability can only be achieved when the three dimensions are improved simultaneously and not only one by itself (Wang & Lin, 2007). One prominent illustration of this are the United Nations Sustainable Development goals, which unite the three dimensions and advocate for joint development in all three of them.

In practice, the environmental, social, and economic dimensions of sustainability are mostly considered separately (Budsaratragoon & Jitmaneeroj, 2019; Svensson, Ferro, Hogevold, Padin, Carlos Sosa Varela & Sarstedt, 2018). Despite the large consensus on the relevance of the three pillars, there is little attention paid to their interrelations (Svensson et al., 2018). A causality implies that a change in one of the three pillars does not only lead to an equal change in overall sustainability but also affects the other pillars and therefore may lead to a much smaller or larger effect in overall sustainability. Researchers have found evidence of causalities including all three pillars of sustainability. However, not all findings are consistent (cf. Figure 1.1).

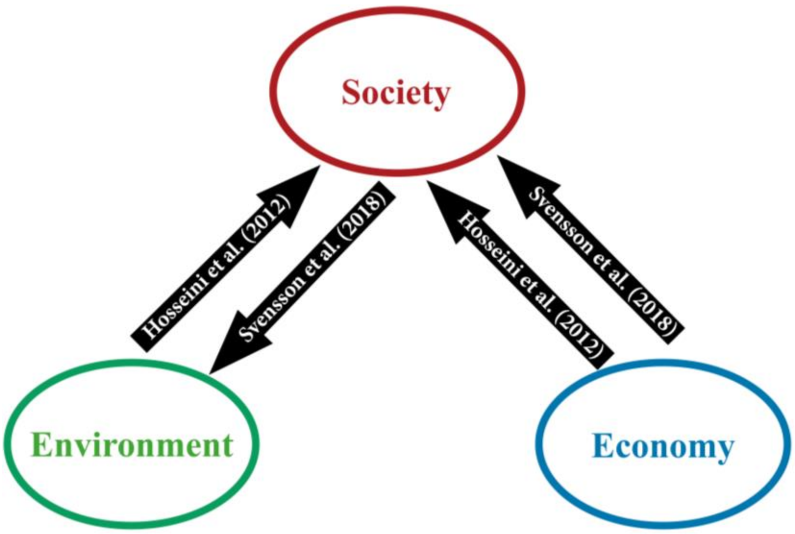


Figure 1.1: Examples of Causal Relationships Found in Previous Studies.

Understanding these causalities is relevant for understanding the effects that a change in practices has. In other words, the understanding of causalities between the pillars of sustainability allows for designing more effective strategies to attain sustainability targets (Mirshojaeian Hosseini & Kaneko, 2012). For this reason, causalities between the pillars of sustainability need to be understood more nuanced (Hammer & Pivo, 2017). Against this backdrop, this study takes thus a closer look at the impacts of changes in social and economic sustainability on environmental sustainability in urban environments. These causal relationships are of particular interest as previous studies are not unequivocal on the causality of social on environmental sustainability, and no causality has been detected between economic and environmental sustainability. Furthermore, these causal relationships reflect the impact of variables where usually higher values indicate more sustainability (socio-economic variables) on variables where lower values mean more sustainability (environmental variables). The associated research question is:

What is the causal effect of socio-economic sustainability on environmental sustainability in cities?

1.2 Aim and Scope

By answering the research question, this study aims to contribute to achieving a better understanding of the causal relationship that exists between the pillars of sustainability in urban environments. From the evidence of previous studies and by intuition, it is expected that this causality is statistically significant. Through the results of the formal analysis of the topic, local actors can improve the predictions they make on the consequences of their decision. The insights can be used to design policies and projects that optimally affect the dimensions of sustainability they are targeting and reduce inefficiencies. Furthermore, the causalities can be incorporated into existing indices, allowing them to report more accurate scores.

The study uses a sample of 60 German cities. The panel of data stretches over the years 2000 to 2013 and includes 33 variables. 21 social, 4 economic, and 4 environmental indicators create the set of explanatory and explained variables. Their data has been collected from the Eurostat Cities Database (2022) and the Regionaldatenbank Deutschland (2022). To quantify the causal effect of socio-economic indicators on environmental indicators, a shock-based instrumental variables (IV) approach is applied. The shock-based IV method has been chosen because OLS estimates introduce an endogeneity problem due to simultaneity bias. After verifying the fulfilment of the conditions that must be fulfilled to apply a shock-based IV approach, the analysis has been conducted on 6 social, 4 economic, and 4 environmental indicators. The global financial crisis that started in 2007 (hereafter 'the financial crisis') serves as the shock since it directly and heavily affected the economic and social dimensions of sustainability but only indirectly had an impact on environmental indicators.

1.3 Outline of the Thesis

This study is divided into six chapters. After this introduction, Chapter 2 gives an overview of the existing literature in the field of city sustainability and the theoretical framework. The literature review focuses on the definition of urban sustainability, the different approaches that can be taken to the concept and a series of methods that are used for city sustainability assessment (SA). Chapter 3 provides information on the choice of indicators as well as the sources which provided the data for these indicators. It further justifies the chosen selection of cities and study period and offers a transparent evaluation of the reliability and representativeness of the data. Chapter 4 introduces the methods. This includes an elaboration on the problem of simultaneity and a background on the shock-based IV approach. Thereafter, Chapter 5 presents and critically discusses the results of the quantitative analysis of the estimated causal effect. Furthermore, the limitations that this study faces are discussed. Finally, the conclusion summarizes the most important insights gained from this study and proposes topics for future studies.

2 Previous Research and Theoretical Framework

The global population is becoming increasingly concentrated in cities (Hobbie & Grimm, 2020). While in 2009, half of the global population lived in urban environments, this number is expected to increase to 70 percent by 2050 (Raworth, 2017). In addition, cities have a crucial economic role. Approximately 80 percent of global GDP is generated in cities (UN-Habitat, 2022). This makes cities an increasingly important actor in fighting climate change (Ahvenniemi et al., 2017) and studying sustainable cities has become a relevant subfield of the sustainability literature. While urbanisation offers numerous positive agglomeration effects, such as increasing returns to scale on investment infrastructure or accumulation of knowledge and skill (Mori & Yamashita, 2015), current trends of urban development also lead to several problems. Within cities, waste, pollutants, and high consumption of non-renewable resources damage the environment, education and elderly care create social challenges, and poverty and unemployment restrain the economy (Kaur & Garg, 2019; Li & Yi, 2020). Beyond their borders, cities cause negative externalities that pose a serious threat to environmental conservation (Mori & Christodoulou, 2012). Furthermore, the risks of climate hazards increase in cities. The reason for this is that certain characteristics of cities can interact with the hazards in a way that aggravates them in urban environments (Hobbie & Grimm, 2020). Studying sustainable ways for cities to develop allows for elaborating practical strategies that can be applied by policymakers and other local actors.

This chapter gives an overview of the previous research in the field of city sustainability and the theoretical background of this study. First, the definition of urban sustainability that is used hereafter is derived from previous studies. Second, different concepts that are discussed in city sustainability literature are explained and compared. Third, a closer look is paid at common assessment methods of city sustainability and the Doughnut model is introduced. Furthermore, a list of deficiencies in indicator assessment is provided.

2.1 Defining Urban Sustainability

So far, literature has not found a consensus on the definition of sustainable development (Holden, Linnerud & Banister, 2014). The most agreed-upon definition stems from ‘Our Common Future’, also known as the Brundtland Report, and states that “[s]ustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (World Commission on Environment and Development, 1987, p.41) As this definition leaves much room for interpretation, literature also does not agree upon one definition of sustainable cities. An early and similarly broad suggestion by Castells (2000, p.118) defines a city as sustainable "if its conditions of production do not destroy over time the conditions of its reproduction". More recently, definitions of urban sustainability are based on the coordinated development of environmental, economic, and social dimensions (Mori & Yamashita, 2015; Shmelev & Shmeleva, 2019). For example, according to Shmelev and Shmeleva (2018, p.904), "[u]rban sustainability is defined as the multidimensional capacity of a city to simultaneously operate successfully in economic, social, and environmental domains".

Definitions of city sustainability, or sustainability in general, also depend on the perspective that is chosen. One crucial distinction is whether a good performance in the social or economic dimensions can balance out worse performance in the environmental dimension. An illustration of the two fundamental views is shown in Figure 2.1. Those arguing that substitution is possible are advocates of 'weak sustainability' (Wilson & Wu, 2017). This approach has already been put forward by Solow (1986), who discussed the question of how much of the world's resources can be used and how much need to be left for future generations. In this context, he supported the view that human capital can substitute for environmental capital. This perspective is widely accepted and adopted by different actors (Folke et al., 2011). The graphic representation of weak sustainability (cf. Figure 2.1, left) shows a triangle that encompasses the three dimensions of sustainability. The closer an actor moves to one of the corners of the triangle, the more the dimension on the opposite side of this corner is substituted for. For example, close to the top corner, hardly any aspects of environmental sustainability are present, but as it is still within the triangle of sustainability, it is considered sustainable. This view is opposed by the view of 'strong sustainability', which "regards natural capital as providing some functions that are not substitutable by man-made capital" (Cabeza Gutés, 1996, p.147). In other words, strong sustainability sees environmental sustainability as a fundamental necessity for social or economic sustainability and the relationship between these pillars is complementary (Wu, 2013). Graphically, the strong sustainability approach puts environmental sustainability at the foundation. Social and economic sustainability can only grow when this foundation is present (cf. Figure 2.1, right). Certain advocates of the strong sustainability perspective, such as Folke et al. (2011), criticise the weak sustainability approach as a mental disconnection between socio-economic progress and environmental well-being. For them, it is crucial to avoid this mental disconnection

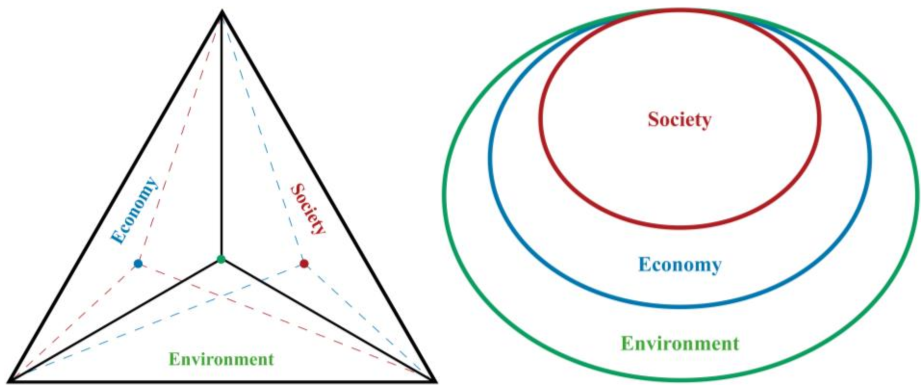


Figure 2.1: Illustration of Weak (Left) and Strong (Right) Sustainability (author's illustration, based on Wu, 2013, p.1002).

because they argue that there are strong dynamics between the different dimensions of sustainability. If environmental well-being remains disconnected from social and economic development, the life-supporting ecosystems of the planet are endangered.This study approaches city sustainability from the perspective of strong sustainability. It considers the environmental dimension of sustainability as fundamentally necessary for overall sustainability and advocates for simultaneous development of the three dimensions of sustainability. Compensations of worse performance in one of the dimensions with better performance in another are not considered sustainable. In this light, the used definition of a sustainable city has been taken from Mori and Yamashita (2015) who state that:

> [a] sustainable city is defined as the city that maximises socio-economic benefits measured by economic and social indicators under relevant constraints measured by environmental sustainability indicators and socio-economic indicators of distributional equity. (Mori & Yamashita, 2015, p.12)

The strength of this definition is its reference to environmental constraints that must not be transgressed and socio-economic necessities that need to be maximized. All three dimensions have their needs that must be fulfilled, which corresponds to the approach of strong sustainability.

2.2 Sustainability Concepts in Cities

City sustainability has been researched since the early 1990s. Over time, a large number of different concepts on the topic have appeared. Being aware of the various existing concepts, how they relate to each other and which one is applied in given contexts allows one to better understand assumptions and principles that guide reasonings. Through a bibliometric study, Fu and Zhang (2017) have analysed the importance of different concepts. According to the authors, the most relevant in literature are the ‘sustainable city’ and the ‘smart city’. Additional concepts they have found to be covered by a considerable share of literature are the ‘eco-city’, the ‘low-carbon city’, and the ‘green city’. They have further found that the level of attention that each of these concepts attracted also differed depending on region and time. The term ‘sustainable city’ is the oldest and most persistent. On a geographical level, its focus lies in America. Discussions of ‘smart cities’ on the other hand appeared at the beginning of the 21st century and are most prominent in Europe. The ‘eco-city’ and ‘low-carbon city’ are dominant concepts in Asia, especially in China, and receive relatively little attention in other regions.

The previously mentioned concepts do not present an exhaustive list of all concepts that exist. Further concepts range from ‘resilient cities’ to ‘knowledge cities’ to ’15-minute cities’, and many more. This review of existing concepts does not go into the details of all these concepts. However, being aware of the large number of different concepts that are proposed in literature illustrates the great heterogeneity that dominates the discussion about sustainable cities. The following sub-sections give an overview of the most discussed concepts in city sustainability. Those are the concept of sustainable cities, which is closely related to the triple bottom line and which builds the foundation of this study, and the smart city concept, which attracts the most attention in literature today.

2.2.1 Sustainable Cities and the Triple Bottom Line

The concept of ‘sustainable cities’ is the most traditional one in the field of urban sustainability (Fu & Zhang, 2017). In the field of urban sustainability in general, many authors underline the need for a holistic approach to sustainability (Cohen, 2017; Kaur & Garg, 2019; Phillis, Kouikoglou & Verdugo, 2017; Yigitcanlar et al., 2019). Among the researchers following the concept of ‘sustainable cities’, an often reappearing and widely accepted picture is the one of an ecological-social-economic triangle, which is known as the triple bottom line (TBL) (Fu & Zhang, 2017; Wilson & Wu, 2017). The TBL is consistent with the perspective of strong sustainability as it considers the three dimensions as complementary and asks for a proportionate emphasis on all three. However, it also differs from strong sustainability in that it does not put environmental sustainability at the foundation, but considers all three dimensions as fundamentally necessary. Sustainability is only reached when each of the three dimensions is sustainable (cf. Figure 2.2). Such an approach is necessary to coordinate the development of these dimensions, which in turn allows cities to develop sustainably (Li & Yi, 2020).

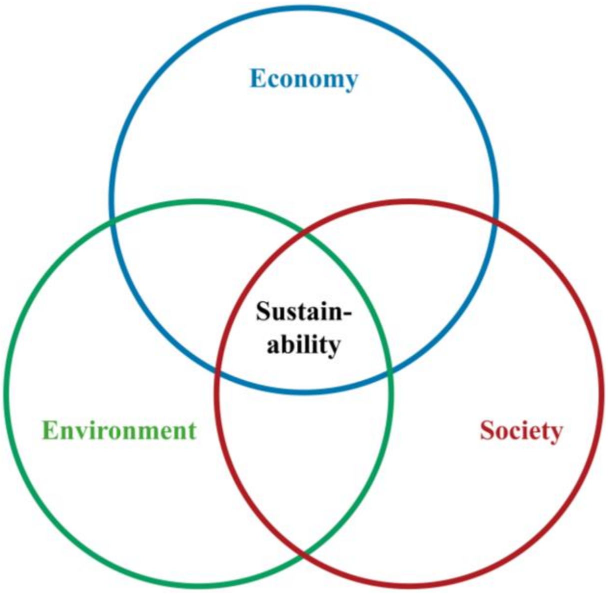


Figure 2.2: Illustration of the Triple Bottom Line (author's illustration, based on Wu, 2013, p.1002).

While there is a large consensus that sustainability is composed of the three pillars of environment, society, and economy (Wilson & Wu, 2017), various scholars have proposed to include further pillars into the TBL. Examples are a culture pillar (Almeida, Ramos & Silva, 2018), a political-institutional pillar (Kaur & Garg, 2019), or a governance pillar

(Budsaratragoon & Jitmaneeroj, 2019). The aim behind the addition of those dimensions is to capture an even more encompassing picture of urban sustainability. However, currently, the dominant approach is limited to the three pillars of environment, society, and economy literature (see for example: Ahvenniemi et al., 2017; Cohen, 2017; Kawakubo et al., 2018; Li & Yi, 2020; Mori & Yamashita, 2015; Yigitcanlar et al., 2019).

The three pillars are also visible in the principles of sustainable cities. Sodiq et al. (2019) have reviewed 192 articles and have found nine principles that act as criteria for a city to be considered sustainable. (1) Sustainable cities provide sustainable education by addressing sustainability topics in curricula and by offering higher education degrees in sustainable development (Sodiq et al., 2019). This is an effective tool as student communities are the most active agents in sustainably transforming European cities (Russo & Tatjer, 2007) and have been found to positively influence political and civil participation for sustainability in a study on US cities (Portney & Berry, 2010). (2) Sustainable cities implement renewable energies. Local governments can ensure sustainable grid-connected systems through policies and encourage a stronger off-grid system by offering financial incentives (Abdmouleh, Alammari & Gastli, 2015; Sodiq et al., 2019). (3) In sustainable cities, the energy sector is efficient. Higher energy efficiency brings numerous benefits beyond sustainability, such as higher energy security, lower energy prices, and further macroeconomic development (Sodiq et al., 2019). (4) Sustainable cities ensure the sustainability of buildings. New constructions can follow the principle of circular economy and avoid materials with relatively high environmental footprints. (5) Sustainable transportation systems take a broad approach to sustainability. Choosing more sustainable means of transport and reducing the environmental footprint of cars and buses might be the more obvious transitions that are necessary for sustainable cities. However, not only the means of mobility are to be considered, but also city logistics, intelligent system management and liveability (Goldman & Gorham, 2006). (6) Sustainable cities address food waste and encourage behavioural changes (Sodiq et al., 2019). Especially households are responsible for a considerable part of food waste (Quested, Parry, Easteal & Swannell, 2011). However, changing behaviour and habits is a difficult challenge for cities. What cities at least need to ensure is the proper disposal of food wastes through the presence of food waste disposers that divert food wastes from landfills (Sodiq et al., 2019). (7) The world – and cities in particular – are confronted with substantial population growth (UN-Habitat, 2021a). Sustainable cities engage in improved efficiencies in areas such as energy or agriculture to deal with growing populations. Furthermore, they support people, especially in developing countries, to reduce unwanted births (Ezeh, Bongaarts & Mberu, 2012). (8) In sustainable cities, ecological units that are required to be preserved for future generations are protected (Sodiq et al., 2019). (9) Sustainable cities limit their environmental footprint in water use, which is greatly exceeded in some cities (Koop & van Leeuwen, 2017). Improved wastewater management can be an effective tool for reducing water use and increasing water security (Sodiq et al., 2019). These nine principles are not necessarily exhaustive but offer an overview of the core values of sustainable cities. Furthermore, these principles are consistent with the TBL. While at first sight, they mostly represent environmental and social sustainability, the economic dimension is inherent to most of them through the creation of more sustainable markets.

2.2.2 Smart Cities

The ‘smart city’ has become the most researched concept in the field of city sustainability, especially in Europe (Fu & Zhang, 2017). The notion of ‘smart city’ first appeared in the 1990s (Gibson, Kozmetsky & Smilor, 1992; Yin, Xiong, Chen, Want, Cooper & David, 2015) and has become its own area of scientific enquiry in 2009 (Mora, Bolici & Deakin, 2017). In recent years, publications on smart cities have increased substantially (Mora, Bolici & Deakin, 2017). However, as for city sustainability in general, no consensus has been established about the definition of smart cities so far. Many studies put it in close relationship with the growing information and communication technologies (ICTs) and new technological innovations (Ahvenniemi et al., 2017; Bibri & Krogstie, 2017; Thornbush & Golubchikov, 2021; Yigitcanlar et al., 2019). Through ICTs, smart urban environments with increased efficiencies and liveability are created (Thornbush & Golubchikov, 2021). The discourse on ‘smart cities’ is closely related to the one on city sustainability. According to Yititcanlar et al. (2019) cities cannot be smart without being sustainable. However, not all researchers agree on this. Among the authors who disagree, there is the perception that cities have started to strive for being smart, not sustainable (Ahvenniemi et al., 2017). In comparison to other concepts concerning city sustainability, ‘smart cities’ have a stronger focus on socio-economic sustainability and a weaker focus on environmental sustainability (Ahvenniemi et al., 2017; Fu & Zhang, 2017). This is for example visible in smart city assessment, where environmental indicators are often lacking (Ahvenniemi et al., 2017). The disagreement on whether smart cities are automatically sustainable can at least partially be ascribed to the discrepancy between weak and strong sustainability. The critique of prioritizing smartness over sustainability indicates a critique of prioritizing economic growth rather than sustainable development (Haarstad, 2017). In other words, Yititcanlar et al.‘s (2019) consideration that cities cannot be smart without being sustainable is more oriented towards weak sustainability, where increased socio-economic smartness can substitute for lower environmental sustainability. A further critique on the smart city concept is that it depends on digital information technologies to improve social and economic performance (Fu & Zhang, 2017). There is a considerable number of researchers criticising this heavy technocentric approach, which neglects solutions that are not technology-based (Yigitcanlar et al., 2019).

2.3 Sustainability Assessment in Cities

Sustainability assessment (SA) is an important part of many sub-fields of sustainability, city sustainability is one of them. In practice, city SA often follows the indicator approach. In other words, the assessment consists of a selection of indicators, through which a final score is calculated that is then used to rank and compare cities (Cohen, 2017). This is a suitable approach because it enables a global consideration of the topic (Phillis, Kouikoglou & Verdugo, 2017). On one hand, it allows to implement the previously discussed concepts and supports policymakers in their decision making process and policy development (Sala, Ciuffo & Nijkamp, 2015). Furthermore, it is a useful tool for comparisons between cities on a national, regional, and global scale.

There is a large variety of city sustainability indices. Some of the internationally established ones are the City Prosperity Index (UN-Habitat, 2021b), the ISO 37120 standard for sustainable cities (World Council on City Data, 2022), and the Safe Cities Index. All of them are using different combinations of indicators, with varying weights assigned to each of them. In addition, literature provides numerous further possible combinations of indicators (Cohen, 2017). In other words, this means that there's a great diversity of opinions on city sustainability indices. The danger of this is that conclusions reached by studies applying indicators heavily depend on the choice of indicators and their weighing, which might be a subjective choice by the researchers (Gasparatos & Scolobig, 2012).

2.3.1 Requirements for Sustainability Assessment Indices

According to Mori and Christodoulou (2015), there are three requirements that indices in the context of city sustainability need to respect. (I) City SA indices need to follow the strong sustainability approach. As discussed in Section 2.1, strong sustainability signifies that no substitution between the dimensions of sustainability is possible. Cities must be sustainable in every single one to be sustainable. (II) Indices of city SA need to distinguish between absolute and relative assessment. This can be translated into a differentiation between environmental and socio-economic indicators. Environmental indicators are based on the planetary boundaries, which are absolute boundaries with a specified limit assigned to each one (Rockström et al., 2009). The crucial information is whether or not these boundaries are transgressed and therefore require absolute assessment. Social and economic indicators on the other hand can usually be fulfilled to various degrees in different cities. Their performance can be measured and compared through relative assessment. (III) The leakage effect needs to be considered in city SA indices. Thereby, indices take into account that cities depend on areas outside of their boundaries and therefore are not sustainable independently.

Although crucial, these three requirements are often not fulfilled. Concerning the first requirement, Ahvenniemi et al. (2017) have found that urban SA is mainly based upon environmental indicators. Other indicators covering for example social or economic aspects are often only marginally included. Concerning the second requirement, common approaches to city SA assign scores to selected indicators. With the use of different weights according to the relevance of the indicators, a final score is calculated (see for example: Almeida, Ramos & Silva, 2018; Kaur & Garg, 2019; Li & Yi, 2020). This approach does not contain a differentiation between relative and absolute assessment. Finally, concerning the third requirement, Mori and Yamashita (2015) argue that no existent index of city sustainability considers both direct and indirect leakage effects. The impact of cities beyond their border is not correctly accounted for.

2.3.2 The Doughnut Model

An interesting model to assess and illustrate sustainability is the Doughnut model (cf. Figure 2.2 for the construction of the Doughnut model and Figure A.1 in Appendix A for an example of an assessment using the Doughnut model), which has been elaborated by the British economist Kate Raworth. In connection with the before-mentioned three criteria of SA indices, the Doughnut Model respects at least criteria one and two. First, the Doughnut model on one hand includes environmental indicators that have a certain boundary, also referred to as planetary boundary (Rockström et al., 2009), which must not be transgressed for operating sustainably. Those indicators are located in the outer part of the model. On the other hand, it includes socio-economic indicators which must fulfil a certain threshold to assure sustainability. Those indicators are located in the inner part of the model. If environmental boundaries are not transgressed and socio-economic thresholds are reached, we are in what Raworth calls the 'safe and just space for humanity' (Raworth, 2017). In the graphical representation, this is the doughnut-shaped area between environmental and socio-economic indicators. As it must be operated sustainably in all dimensions to reach this space, the Doughnut model follows the strong sustainability perspective. Second, the use of indicators is similar to Mori and Christodoulou's (2012) constraint and maximization indicators. Constraint indicators include environmental and equity aspects of sustainability and have a limit that must not be transgressed, similar to the environmental indicators in the Doughnut model. Maximization indicators include economic and social dimensions that need to reach a minimum level, similar to the socio-economic indicators in the Doughnut model. Thereby, the second of the above-mentioned criteria is respected.

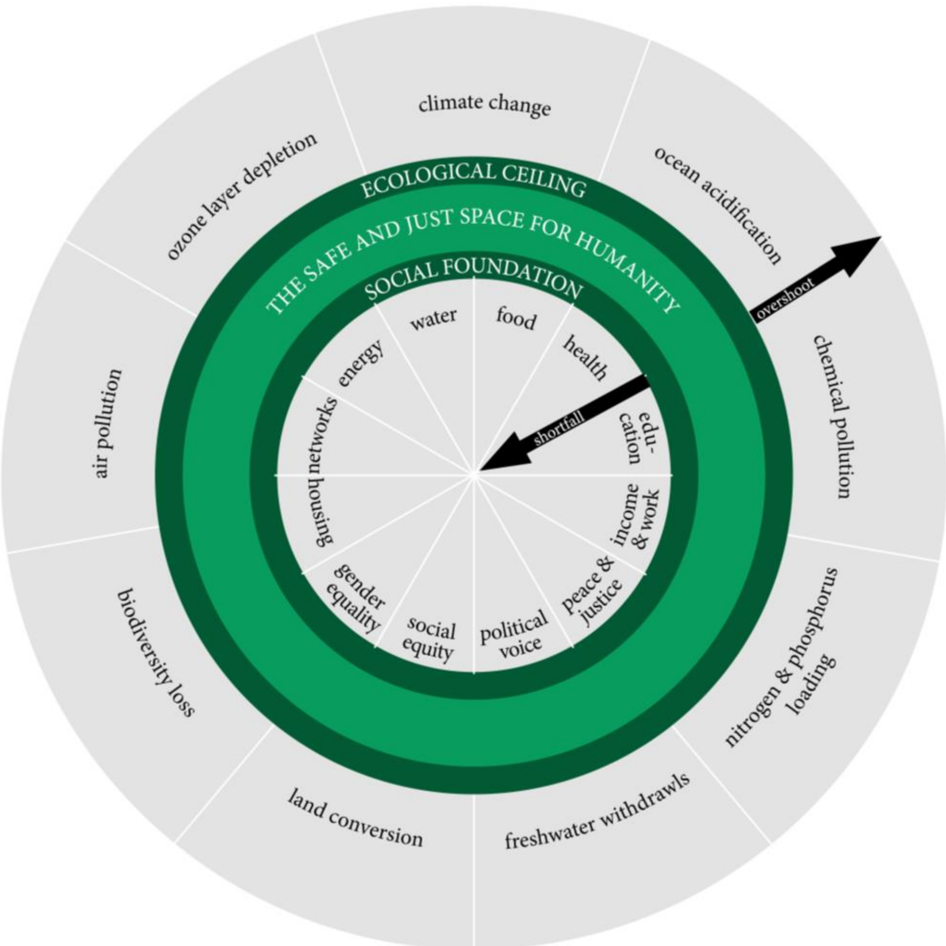


Figure 2.3:The Doughnut Model, as Proposed by Raworth (author's illustration, based on Raworth, 2017, p.50).

Through its strong graphical component, the Doughnut model offers an easily graspable illustration of the included indicators and their performance in a given context. Thereby, it responds to the need for a more practice-oriented approach to sustainability (Cohen, 2017). In the context of city sustainability, the Doughnut model has been applied by a series of cities. Formally, the public administrations in cities such as Cali (Colombia), Amsterdam (Netherlands), Barcelona (Spain), and Nanaimo (Canada) have adopted the Doughnut model in their sustainability strategies (Bareras, 2021; City of Amsterdam, 2020; DEAL, 2022; Gold, 2021). Additionally, many more cities have working teams that apply the Doughnut model on an informal level (DEAL, 2022).

2.3.3 Deficiencies of Indicator Assessment

The contemporary state of the discipline still includes gaps and inconsistencies. A first important gap in contemporary assessment methods is that often they only look at the dimensions of the TBL individually (Budsaratragoon & Jitmaneeroj, 2019; Svensson et al., 2018). By giving scores to each of the dimensions and aggregating them to a final score, it is assumed that the dimensions are independent. There is no measure of causal relationships between the pillars of the TBL, yet it is to be expected that there are some (Budsaratragoon & Jitmaneeroj, 2019; Lee, Geum, Lee & Park, 2012). Although it adds a high level of complexity to the analysis (Mirshojaeian Hosseini & Kaneko, 2012), future studies should focus on filling this gap. Through an understanding of causalities between the sustainability pillars more effective and successful sustainability strategies can be designed (Mirshojaeian Hosseini & Kaneko, 2012). Second, the outcomes of SA strongly depend on the goal and concept that the assessment strategy follows. Researchers need to choose the indicators used, the weight they give them, how they are normalized and how they are aggregated (Phillis, Kouikoglou & Verdugo, 2017). Each of these steps adds a dimension of subjectivity to the practice. Lastly, a fundamental limitation that is shared in the whole field of city SA is the availability of data at the subnational level. National statistics offices and international agencies often focus on data on the national scale (Phillis, Kouikoglou & Verdugo, 2017). Similarly, organizations calculating the established indices mentioned at the beginning of this section often do not provide the data on which their rankings are based. As a consequence, city SA is often limited by partially or fully missing data.

3 Data

The insights that have been gained in previous studies were applied in the selection of indicators and the construction of the model used in this study. This chapter provides a deeper insight into the data that is used in this study. First, the selection and treatment of variables are presented. Second, the process of constructing the city sample and defining a study period is explained. Thereafter, a reflection on the reliability and representativeness of the data is offered. Finally, the limitations that have been induced by data unavailability are recognized.

The data used in this study has been collected from two sources. For all but two variables, the data was taken from the Eurostat Cities Database (2022), which belongs to the database of the European Union (EU) and contains around 60 indicators for more than 1000 European cities. Data for the remaining two variables (*soc_assistance* and *insolvency*) was collected from the Regionaldatenbank Deutschland (2022), which is part of the database of the Federal Statistical Office of Germany. Data were available for all of the 60 chosen cities.

3.1 Selection of Variables

The choice of variables was guided by the Doughnut model (cf. Section 2.3.2) and adapted according to this study's needs and limitations (see Figure B.1 in Appendix B for the illustration of this study's Doughnut model). The list of variables included in this study is presented in Table 3.1. This table further informs about which of the three pillars of the TBL the variable belongs to and whether they are maximazion or constraint variables. The explained variables are those representing environmental sustainability and are all constraint indicators. More precisely, they are *ozone_conc* (the concentration of ozone), *no2_conc* (the concentration of nitrogen dioxide, NO2), and *pm10_conc* (the concentration of particulate matter, PM10), as well as *water_use* (the total use of water). When compared to the Doughnut model, *ozone_conc*, *pm10_conc*, and *water_use* are equivalent to the model's dimensions of ozone layer depletion, air pollution, and freshwater withdrawals. *No2_conc* is not directly included in the model but can be assigned to the dimension of air pollution as well.

The explanatory variables represent socio-economic sustainability. To a large share, they are maximisation indicators. Of the 26 explanatory variables, only *inf_mortality* and *sewerage_con* are identical to those included in the Doughnut model. With the use of alternative indicators, six of the twelve dimensions of the inner part of the Doughnut model are represented in this study. These dimensions and the respective indicators are education (*daycare, hi_educ*), income & work (*unempl_rate, activity_rate*), social equity (*soc_assistance, soc_housing, homeless_acc*), housing (*living_area, house, apartment*), water (*sewerage_con*), and health (*inf_mortality, u65_death*).

Table 3.1: Variables Used in the Analysis.

Category	Variable	Label	Pillar	Type	Norm.
General	*city*	City			
	year	Year			
	pop	Total population			
	postshock	Dummy, 0=before 1=after financial crisis			
Education	*daycare*	Number of children 0-4 in daycare or school	Soc	M	x
	hi_educ	Students in higher education in the total population [%]	Soc	M	x
Mortality / Health	*inf_mortality*	Infant Mortality per year	Soc	C	x
	u65_death	Total deaths under 65 per year	Soc	C	x
Transport	*road_death*	Number of deaths in road accidents	Soc	C	x
	car_journey	Journeys to work by car [%]	Soc	C	
	mcycle_journey	Journeys to work by motorcycle [%]	Soc	C	
	carmcycle_journey	Journeys to work by car or motorcycle [%]	Soc	C	
	pt_journey	Journeys to work by public transport [%]	Soc	M	
	bicycle_journey	Journeys to work by bicycle [%]	Soc	M	
	foot_journey	Journeys to work by foot [%]	Soc	M	
Social support	*soc_assistance*	Number of recipients of social assistance	Soc	M	x
	soc_housing	Number of households in social housing	Soc	M	x
	homeless_acc	Number of people in accommodation for the homeless	Soc	M	x
Housing	*living_area*	Average area of living accommodation [m²/person]	Soc	M	
	house	Number of houses	Soc	M	x
	apartment	Number of apartments	Soc	M	x
Culture	*cinema*	Number of cinema seats (total capacity)	Soc	M	x
	theatre	Number of theatres	Soc	M	x
	library	Number of public libraries (all distribution points)	Soc	M	x
Sanitation	*sewerage_con*	Population connected to sewerage treatment system [%]	Soc	M	
Employment	*unempl_rate*	Unemployment rate	Eco	C	
	activity_rate	Activity rate	Eco	M	
Economy	*companies*	Number of companies in the city	Eco	M	x
	insolvency	Number of insolvency proceedings filed	Eco	C	x
Planetary Boundaries	*ozone_conc*	Accumulated ozone concentration in excess of 70 μg/m³	Env	C	
	no2_conc	Annual average concentration of NO2 [μg/m³]	Env	C	
	pm10_conc	Annual average concentration of PM10 [μg/m³]	Env	C	
	water_use	Total use of water [m³]	Env	C	x

Notes: ‘Pillar’ informs on which of the three pillars of the TBL the variable belongs to (env = environmental, soc = social, eco = economic). ‘Type’ informs whether the variable is a maximisation (M) variable or a constraint (C) variable. ‘Norm.’ informs whether the variable has been normalized to report its value per 1000 persons.

In addition, the dimensions of culture (*cinema, theatre, library*), transport (*road_dearh, car_journey, mcycle_journey, carmcycle_journey, pt_journey, bicycle_journey, foot_journey*), and economy (*companies, insolvency*) were added in this study, as their relevance has been put forward in city sustainability literature.

A few changes were made to the selected data. First, 93 out of 840 observations of the total city population were missing and have been estimated. Although estimating results may introduce a bias, this is a common practice in the construction of composite indicators (OECD, 2008) and it was a necessary step for the following normalization of the variables. Second, a series of variables was normalized to report values per 1000 persons. Thereby, comparability among cities has been improved. Which variables were affected by this normalization can also be seen in Table 3.1. Third, observations of the variables from the Regionaldatenbank Deutschland were deleted for five cities. The reason for that is that the reported population size for these cities differs severely when comparing the Regionaldatenbank and the Cities Database.

3.2 Selection of Cities and Study Period

The initial approach of this study was to focus on European cities. The choice of this region was based on two main reasons. First, causal relationships differ heavily between countries and regions (Mirshojaeian Hosseini & Kaneko, 2012), especially between developed and developing countries (Kawakubo et al., 2018; Mirshojaeian Hosseini & Kaneko, 2012; Phillis, Kouikoglou & Verdugo, 2017). As a consequence, taking a global approach would likely have led to weak outcomes that are too general to be representative of different regions. Second, data availability and quality are relatively high in Europe, when compared to cities in other regions.

However, in the process of the study, it was further necessary to limit the city sample to only German cities. Large numbers of missing observations across all variables made it impossible to obtain a representative sample of all European cities. The relatively extensive data collection in Germany has been noticeable, for which reason 60 German cities have been selected for this study. The criteria that each city needed to fulfil to be selected into the sample were that it needed at least six variables with data reported and this data needed to contain two or more observations for the years between 2000 and 2006, as the earlier years tended to have fewer observations. The list of cities can be found in Table B.1 in Appendix B. Data availability also affected the studied period. The Eurostat Cities database, which supplies most of the data used, has sufficient amounts of data between 2000 and 2013. After 2013, there is an abrupt cut and too few cities reported observations for many of the indicators. As a consequence, the panel used in this study includes observations for each indicator for the years from 2000 to 2013.

3.3 Reliability and Representativeness of the Data

The sample of German cities includes 60 cities, of which there is at least one per German state. The cities' populations reach between 50'000 and 3'500'000 inhabitants. According to the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), in Germany, cities are defined as settlements with more than 5'000 inhabitants, or settlements with a central function (BBSR, 2022). This indicates that the city sample may not be representative of smaller cities (5'000 to 49'999 inhabitants), as they are not included in the sample. A more detailed analysis of this follows in the discussion in Chapter 5.

The reliability and representativeness of the data are favoured by the fact that most of the data comes from one single database and is, therefore, more comparable than data from multiple sources. The comparability of the two data sources has been confirmed before using the second source.

3.4 Limitations through Data Unavailability

Data unavailability largely impacted the data collection process. Data at the city level is rarer than at the national level and includes significantly more missing observations. Even cities that collect data for given indicators often do so irregularly, which makes constructing a panel dataset for a quantitative analysis a challenging task. One reason for missing observations in the Eurostat Cities database is that EU members are not legally required to collect and provide data at the city level but do so voluntarily (Eurostat, 2022). For the present study, the two sources that have been chosen were those with the highest number of observations for indicators relevant to this study. However, it is important to note that still, certain indicators had to be dropped in the selection process, which possibly introduced a selection bias. As a consequence, the environmental and socio-economic parts of the Doughnut model have not been fully adopted in this study.

The data that is included in the panel used for this study is expected to be of good quality. This assumption is made based on the professional collection of the data either by Eurostat or by the Federal Statistical Office of Germany. Hence, the quality threats are not expected to be introduced by data included in the study but rather by the missing data.

4 Methods

This chapter discusses the methods that are applied in this study. First, the endogeneity problem of simultaneity bias and possible solutions are discussed. The second part introduces the method that has been chosen to deal with the simultaneity bias and estimate the causal effect of interest. This method is a shock-based instrumental variable (IV) method, where a shock that affected socio-economic, but not environmental, indicators is applied as an instrument. Conditions to the application of the method are discussed and a justification of the chosen shock, the financial crisis, is provided. Finally, the model equations are presented.

4.1 The Problem of Simultaneity

This study is based on the hypothesis that social and economic sustainability improve environmental sustainability. For this reason, analysed regressions aim to quantify the causal effect that socio-economic indicators have on environmental indicators. However, it is likely that causality not only goes from socio-economic to environmental indicators but also the other way around. For example, Mirshojaeian Hosseini and Kaneko (2012) have analysed causal relationships between environmental, social, economic, and institutional sustainability. In their study, they have found a positive causal effect of environmental on social sustainability in both OECD and non-OECD countries. Such a causal relationship introduces an endogeneity problem. More specifically, OLS estimates are biased due to simultaneity. As a consequence, the analysis needs to apply a method that can isolate the causality from socio-economic sustainability to environmental sustainability from the one in the inverse direction.

Some of the possible methods are presented hereafter. First, each explanatory variable that is affected by the reverse causality can be replaced with an instrument that is not affected. The requirements that instruments need to fulfil are that (I) they must have a causal effect on the explained variable, (II) they are not related to unobserved variables, and (III) the causal effect of the instrument on the explained variable only goes through the instrumented variable (Angrist & Pischke, 2015). Finding suitable instruments that fulfil all requirements and for which data is available is challenging. Concerns about poor quality instruments have also been raised by Clemens, Radelet, Bhavani and Bazzi (2012) who instead replaced values with their lagged values to deal with simultaneity bias. The two conditions for effective estimations with lags are that “(I) the lagged values do not themselves belong in the respective estimating equation and (II) they are sufficiently correlated with the simultaneously determined explanatory variable”(Reed, 2015, p.898). A third method is to apply a regression discontinuity (RD) design. This method uses a shock that occurred within the observed period and that affected explanatory, but not explained variables. Thereby, the causal effect from the explanatory to explained variable can be isolated from the reverse causality.

4.2 Shock-based Instrumental Variable Approach

This study applies a combination of two of the above-mentioned methods, IV and RD. More specifically, a shock-based instrumental variable approach is applied to avoid a simultaneity bias on OLS estimates. The core of the method consists of using an exogenous shock that occurred during the study period as an instrument in a two-stage least-squares (2SLS) estimation. In a first step, the relationship between the shock and the explanatory variables is analysed. Thereafter, it needs to be established that the shock has no direct impact on the indicators of environmental sustainability. Finally, the 2SLS estimations can be performed to quantify the causal effect of socio-economic sustainability on environmental sustainability. The following paragraphs give a short overview of the two methods, IV and RD, and their conditions, as well as a justification of the choice of shock.

4.2.1 Instrumental Variables

The IV method consists of replacing the endogenous explanatory variable with an instrument that is not affected by endogeneity. To obtain unbiased IV estimates, four conditions need to be fulfilled. First, there needs to be a strong first stage, indicating that the effect of the instrument on the instrumented variable is strong. This can be tested through an OLS regression. A general rule of thumb defines an F-statistic that is larger than 10 as a strong enough effect (Angrist & Pischke, 2015). Whether this assumption is fulfilled in this study is tested in the first step of the empirical analysis in Chapter 5.

Second, the independence assumption must hold. This assumption states that the instrument is uncorrelated to all unobserved determinants of the explained variable. As there is no formal test to check whether the independence assumption holds, it needs to be analysed with insights from previous studies and intuition. In this study, it is expected that the only correlations between the financial crisis and the environmental indicators are captured by the socio-economic indicators. A wide variety of socio-economic indicators were chosen with the aim of capturing all correlations. However, a weakness is introduced by the need of running individual regressions for each explanatory variable. This need was created by the fact that each socio-economic variable was expected to be affected by simultaneity and therefore had to be instrumented for by the shock. As a consequence, there is the possibility that the independence assumption does not hold.

The third condition is the exclusion restriction, which states that the entire channel of causality from the instrument to the explained variable goes through the instrumented variable. As for the independence assumption, there is no formal test to ensure that the exclusion restriction is respected. For this study, a qualitative analysis of opinions in literature is also difficult, as research on the impact of the financial crisis on the environment is rather scarce. Several studies on different financial crises have found impacts such as decreasing CO_2 emissions, energy consumption, and air pollution, as well as lower water and soil quality (Pacca, Antonarakis, Schröder & Antoniades, 2020). However, it is logically coherent to assume that the environmental impacts have been caused through the channel of socio-economic impacts. For example, decreasing CO_2 emissions have not been a direct effect of the financial crisis, but rather a consequence of reduced economic activity and changes in behaviour. These effects are captured in socio-economic indicators such as the unemployment rate or variables related to the amount of public spending that benefits and protects the environment. As a consequence, it is assumed that the exclusion restriction is respected.

Fourth, the monotonicity assumption states that there are no defiers in the sample. Defiers are individuals who act as if they were treated when they were not, and do not act as if they were treated when they were treated. For the current study, this means that no city has behaved like being affected by the financial crisis when they were not affected and not behaved like such when they were affected. This scenario is unlikely because the financial crisis has been an exceptionally strong shock that has been felt in many dimensions. Cities behaving like they have not been affected by such a strong shock when actually they have is not likely.

4.2.2 Regression Discontinuity

Regression discontinuity, or RD, is closely related to IV, it can even be thought of as an extension of IV (Oldenburg, Moscoe & Bärnighausen, 2016). There are two subcategories, namely sharp and fuzzy RD. The former assigns treatment in an absolute manner (yes or no), while for the latter, the likelihood of treatment increases at the threshold. Cities were affected by the financial crisis in an absolute manner, when the financial crisis hit, all of them were affected with a probability equal to one. For this reason, this study applies a sharp RD design. Angrist and Pischke (2015) state that it is necessary to find an external shock, or treatment, that affects the explanatory variable(s) but not the explained variable(s). The treatment is included in the regression equation in the form of a dummy that is equal to one when treatment is obtained and zero otherwise. (Angrist & Pischke, 2015)

As previously discussed, the shock in this study is the financial crisis. The financial crisis has affected a wide range of social and economic indicators. Ötker-Robe and Podpiera (2013) have found that it caused higher unemployment, increased poverty and the erosion of savings, interrupted the provision of essential public goods and services, reduced school enrolment rates, deteriorated health conditions, and increased suicide rates. Even stronger were the impacts on economic indicators. Among them were a severe break in real GDP growth, contractions of bank credits or reductions in private investment (Makin, 2019). The threshold of the shock has been chosen between the years 2007 and 2008. The reasoning for this choice is that, although the first impacts of the crisis have been felt in late 2007 (Ötker-Robe & Podpiera, 2013), it is expected that the 2007 data still represents a large share of unaffected data. Furthermore, it may take some time for the shock to be shown in the data of the chosen indicators. Data for the year 2008 however is expected to be affected. This intuition is supported by Ötker-Robe and Podpiera (2013) whose graphs on different indicators show a significant kink starting in 2008. For this reason, data for the years 2008 and onwards make up part of the post-shock period in this study.

4.3 Regression Equations

As all chosen variables might be affected by reverse causality and the shock of the financial crisis has been used as the instrument for all of them, it is not possible to include all variables in a single model. For this reason, individual regressions are necessary for each combination of socio-economic and environmental indicators. Equation (1) represents the first stage and equation (2) the second stage of the shock-based IV model used in this study.

(1) $[\textit{social or economic indicator}]_{i,t} = \alpha_0 + \alpha_1 \textit{ postshock} + e_{i,t}$

(2) $[\textit{environmental indicator}]_{i,t} = \beta_0 + \beta_1 [\textit{social or economic indicator}]_{i,t} + u_{i,t}$

The term [social or economic indicator]$_{i,t}$ stands for any social or economic indicator for city i in year t and [environmental indicator]$_{i,t}$ stands for any environmental indicator for city i in year t. α_0 and β_0 are the constants of the respective equations. α_1 is the coefficient of the post-shock variable and estimates the strength of the shock on the social or economic indicator in question. β_1 is the coefficient of the social or economic indicators and estimates the causal effect that each indicator has on the environmental indicator. *Postshock* is the dummy that is equal to one after the shock of the financial crisis and zero otherwise, and $e_{i,t}$ and $u_{i,t}$ are the error terms of the respective equations.

5 Empirical Analysis

This chapter presents and discusses the results of the empirical analysis. In the first section, the descriptive statistics, as well as the results of the shock-based IV approach, are presented. Thereafter, the second section discusses the results and highlights their implications. Finally, the third section discusses the limitations that this study faces.

5.1 Results

The first results presented are the descriptive statistics. Due to limited space, only the explanatory variables that have later on qualified for the IV estimation (those with a large F-statistic) are discussed here. The statistical justification for the qualification for the IV estimation is given in the second sub-section, where the relationships between the explanatory variables and the shock are analysed. Numerical results are supported with graphical illustrations. For completeness, the graphical illustrations are also supplied for the relationship between the explained variables and the shock. Finally, the 2SLS estimates of the causal effect of the socio-economic indicators on the environmental indicators are presented.

5.1.1 Descriptive Statistics

Table 5.1 provides the descriptive statistics of the 34 variables included in this study. Of the variables that have qualified for the IV-analysis, the most observations are available for the two variables from the Regionaldatenbank Deutschland, *insolvency* and *soc_assistance*. For them, there are 756 observations over the 14 years available. Many of the remaining variables have approximately 650 observations. Significantly fewer observations are available for *soc_housing* with 423 observations. The likely consequence of more missing observations are weaker results. Whether this is the case in this study is discussed in Section 5.2. Concerning the standard deviations of the variables, there are two noticeable outliers. On one side, *activity_rate* reports a much smaller standard deviation in relation to its mean than all other variables. On the other side, *soc_assistance* has a relatively large standard deviation. The range between the variables' minima and maxima is strongly related to the standard deviations. This suggests that the observations are spread over the whole range and there are less outliers. The exception is *road_death*, where the range is exceptionally large.

The explained variables on average have more observations than the explanatory variables. However, the number for *water_use* is also small with 532 observations. The standard deviation with respect to the mean is the largest for *ozone_conc*. Relatively similar values in terms of their mean are reported for *water_use* and *no2_conc*, while *pm10_conc* has the smallest standard deviation. *Water_use* has the largest range of the four environmental variables, which suggests a strong presence of outliers. For the remaining three variables the order of largest to smallest standard deviation corresponds to the order of largest to smallest range, which suggests less outliers.

Table 5.1: Descriptive Statistics.

Variable	**Obs**	**Mean**	**Std. dev.**	**Min**	**Max**
city	60	-	-	-	-
year	840	2006.50	4.03	2000	2013
pop	840	366’463.60	490’164.80	50’365.70	3’460’725.00
postshock	840	0.43	0.50	0	1
High F-stat explanatory variables:					
daycare	651	20.05	4.24	10.98	38.07
inf_mortality	607	0.03	0.02	0.00	0.10
u65_death	640	1.80	0.35	0.35	2.85
road_death	634	0.03	0.02	0.00	0.18
soc_assistance	756	17.90	21.84	0.00	120.18
soc_housing	423	35.47	20.58	0.23	93.96
unempl_rate	658	9.85	4.05	3.00	23.00
activity_rate	657	56.54	3.15	49.00	64.00
companies	641	38.38	11.92	17.09	73.88
insolvency	756	1.77	0.91	0.00	4.68
Low F-stat explanatory variables:					
hi_educ	618	83.16	63.26	0.00	306.00
car_journey	484	55.96	9.75	32.40	80.30
mcycle_journey	394	1.25	0.67	0.20	4.40
carmcycle_journey	454	56.91	9.89	33.60	81.00
pt_journey	454	21.56	8.38	4.30	45.70
bicycle_journey	474	10.53	6.78	0.30	32.90
foot_journey	474	10.34	3.19	5.00	23.40
homeless_acc	244	1.19	1.22	0.00	9.60
living_area	511	39.00	3.31	31.00	48.00
house	634	120.03	38.21	52.41	209.11
apartment	634	416.58	66.75	233.04	586.18
cinema	587	17.30	5.90	4.53	33.06
theatre	641	0.01	0.01	0.00	0.14
library	633	0.07	0.04	0.00	0.22
sewerage_con	563	99.04	1.39	90.90	100.00
Explained variables:					
ozone_conc	740	3’658.30	1’282.09	31.00	10’044.00
no2_conc	746	25.95	6.56	11.37	44.80
pm10_conc	704	22.97	3.93	12.70	36.50
water_use	532	62’037.15	19’734.53	31’689.81	246’616.20

5.1.2 The Relationship Between the Shock and the Social and Economic Indicators

Having examined the descriptive statistics, the analysis proceeds to investigate the relationship between the shock and the socio-economic indicators. The statistical part of this investigation consists of OLS regressions of the socio-economic indicators on the post-shock dummy. Thereby, it was determined whether the shock impacted the variables to a statistically significant degree. The determining factor is the reported F-statistic, which is required to be larger than ten. This step corresponds also to testing the first IV condition (cf. Section 4.2.1). In addition, the analysis has been done graphically through scatterplots with pre- and post-shock trendlines.

The statistical analysis has eliminated a little more than half of the previously selected socio-economic indicators because their F-statistic was too low. The variables with an F-statistic larger than 10 are (1) *daycare*, (2) *inf_mortality*, (3) *u65_death*, (4) *road_death*, (5) *soc_assistance*, (6) *soc_housing*, (7) *unempl_rate*, (8) *activity_rate*, (9) *companies*, and (10) *insolvency*. Estimates of the coefficients of the relationship between the shock and these ten variables are reported in Table 5.2. Estimates of the remaining 15 variables with a low F-statistic are reported in Table 5.3. In a preparatory step, White tests were performed on all variables to test for heteroskedasticity. For those variables where the White tests suggested that they were affected by heteroskedasticity, robust standard errors are reported, while for the remaining variables, common standard errors are reported. The heteroskedastic variables are *daycare*, *inf_mortality*, *soc_assistance*, *soc_housing*, *unempl_rate*, *companies*, *living_area*, and *theatre*.

Table 5.2: OLS Regressions of Social and Economic Indicators on the Post-shock Dummy, Large F-Statistic.

	(1)	(2)	(3)	(4)	(5)
postshock	2.237***	-0.005***	-0.128***	-0.008***	-23.770***
	(0.318)[1]	(0.001)[1]	(0.028)[1]	(0.001)	(1.174)[1]
F-stat	49.55	12.53	20.92	36.04	294.35
_cons	18.850***	0.037***	1.872***	0.031***	28.080***
	(0.214)	(0.001)	(0.023)	(0.001)	(1.169)
N	651	607	640	634	756
	(6)	(7)	(8)	(9)	(10)
postshock	-12.200***	-3.535***	1.093***	5.134***	0.629***
	(1.940)[1]	(0.298)[1]	(0.243)	(0.913)[1]	(0.063)
F-stat	39.57	140.92	20.22	31.64	65.59
_cons	41.880***	11.780***	55.940***	35.580***	1.502***
	(1.562)	(0.258)	(0.180)	(0.630)	(0.041)
N	423	658	657	641	756

Notes: standard errors in parentheses ([1] these are robust standard errors), * p<0.10, **p<0.05, *** p<0.01, variables reported are (1) *daycare*, (2) *inf_mortality*, (3) *u65_death*, (4) *road_death*, (5) *soc_assistance*, (6) *soc_housing*, (7) *unempl_rate*, (8) *activity_rate*, (9) *companies*, and (10) *insolvency*.

The estimates of the impact of the shock are to a large part statistically significant. For the variables in Table 5.2, all estimates are significant at the 99% level, while for those in Table 5.3, about half of the estimates are significant at the 99% or 95% level. The remaining variables with neither a large F-statistic nor a statistically significant estimate of the shock are *mcycle_journey*, *pt_journey*, *foot_journey*, *homeless_acc*, *house*, *apartment*, and *library*.

In terms of their mean, the estimate that suggests the strongest impact of the shock on (5) *soc_assistance*. Further strong impacts are suggested for (6) *soc_housing*, (7) *unempl_rate*, and (10) *insolvency*. The weakest impacts are suggested for (3) *u65_death*, and (8) *activity_rate*.

Table 5.3: OLS Regressions of Social and Economic Indicators on the Post-shock Dummy, Small F-Statistic.

	(1)	(2)	(3)	(4)	(5)
postshock	11.010**	-2.621***	0.060	-2.383**	1.058
	(5.129)	(0.910)	(0.073)	(0.943)	(0.803)
F-stat	4.61	8.29	0.68	6.39	1.74
_cons	76.850***	56.930***	1.233***	57.860***	21.150***
	(3.882)	(0.555)	(0.040)	(0.594)	(0.506)
N	618	484	394	454	454
	(6)	(7)	(8)	(9)	(10)
postshock	1.521**	0.044	-0.163	0.691**	4.828
	(0.639)	(0.303)	(0.157)	(0.317)[1]	(3.060)
F-stat	5.67	0.02	1.08	4.76	2.49
_cons	9.950***	10.320***	1.285***	38.760***	117.300***
	(0.394)	(0.186)	(0.119)	(0.173)	(2.306)
N	474	474	244	511	634
	(11)	(12)	(13)	(14)	(15)
postshock	4.160	-1.244**	-0.002***	-0.000	0.249**
	(5.353)	(0.496)	(0.001)[1]	(0.003)	(0.120)
F-stat	0.60	6.30	7.17	0.01	4.31
_cons	414.200***	18.050***	0.014***	0.065***	98.890***
	(4.034)	(0.385)	(0.001)	(0.002)	(0.094)
N	634	587	641	633	563

Notes: standard errors in parentheses ([1] these are robust standard errors), *p<0.10, **p<0.05, *** p<0.01, (1) *hi_educ*, (2) car_journey, (3) *mcycle_journey*, (4) *carmcycle_journey*, (5) *pt_journey*, (6) *bicycle_journey*, (7) *foot_journey*, (8) *homeless_acc*, (9) *living_area*, (10) *house*, (11) *apartment* , (12) *cinema*, (13) *theatre*, (14) *library*, and (15) *sewerage_con*.

Figure 5.1 provides the graphical illustrations for the ten variables for which the F-statistic was sufficiently large. Each panel contains a scatterplot of one of the ten variables. The blue line is the trendline before the shock, including the years 2000 to 2007, and the orange line is the post-shock trendline, including the years 2008 to 2013. The graphs of the remaining fifteen variables with a low F-statistic are shown in Figure C.1 in Appendix C.

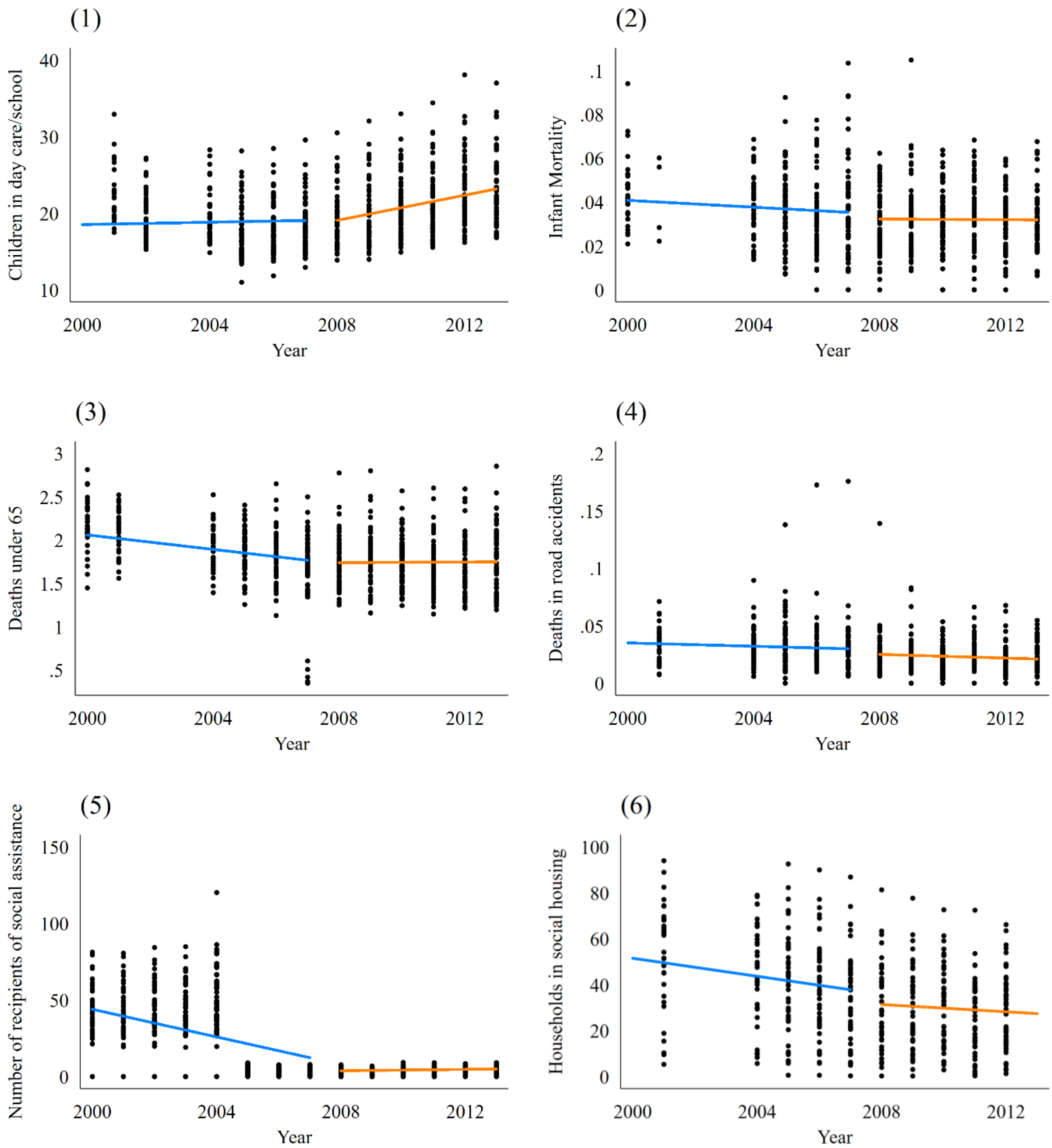
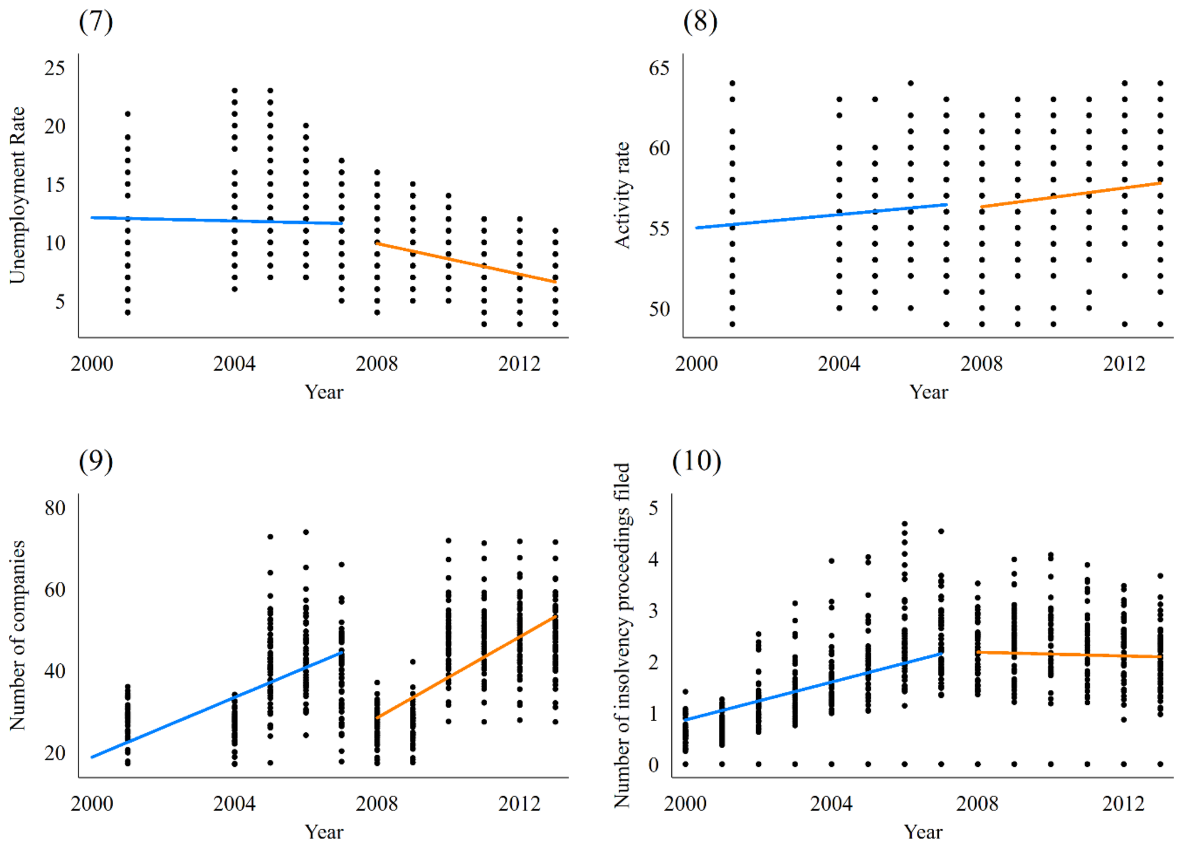


Figure 5.1: Scatterplots for (1) daycare, (2) inf_mortality, (3) u65_death, (4) road_death, (5) soc_assistance, (6) soc_housing, (7) unempl_rate, (8) activity_rate, (9) companies, and (10) insolvency, with linear pre- and post-shock trendline, 2000-2013.



Continuation of Figure 5.1: Scatterplots for (1) daycare, (2) inf_mortality, (3) u65_death, (4) road_death, (5) soc_assistance, (6) soc_housing, (7) unempl_rate, (8) activity_rate, (9) companies, and (10) insolvency, with linear pre- and post-shock trendline, 2000-2013.

Notes: (1), (3)-(6), (9) and (10) are reported in the number per 1000 persons of the total population, (2), (7) and (8) as percentages.

The ten panels in Figure 5.1 suggest three categories of variables in relation to the shock. First, there are strongly impacted variables, namely (2) *inf_mortality*, (9) *companies*, and (10) *insolvency*. For the latter two, the discontinuity is visible in both the trendlines and the individual observations. For (2) *inf_mortality*, the discontinuity is only visible when considering all observations. After the shock, the range decreased, especially at the upper end of the distribution. Second, only small discontinuities are visible for (3) *u65_death*, (4) *road_death*, (6) *soc_housing*, and (8) *activity_rate*. For all of those variables, there are no observations for the years 2002 and 2003. This has likely weakened the prediction of the pre-shock trend. However, even when considering all observations, there is no suggestion that the trendlines hide an effect of the financial crisis. According to the graphical analysis, those variables were hardly affected by the shock. Third, attention is drawn to the year 2005, where three variables suggest a discontinuity. Those variables are (1) *daycare*, (5) *soc_assistance*, and (7) *unempl_rate*. For all three variables, the trendlines suggest a regression discontinuity in 2008. However, when considering all observations and not only the trendlines, it is suggested that the shock already affected observations in 2005. As this is unambiguously before the financial crisis hit, this suggests a misspecification of the shock. A more detailed analysis of this suggestion is provided in Section 5.2.

Many variables either show hardly any discontinuity at the threshold or suggest that the shock has been a different one than the financial crisis and occurred in the year 2005. A certain amount of accuracy might have been lost with the choice of linear instead of non-linear trendlines. For completeness, the discontinuities have also been illustrated with fourth-degree polynomial trendlines (cf. Figure C.2 in Appendix C). However, these trendlines overestimate the discontinuities and are judged to be less accurate than the linear trendlines.

Overall, the analysis of the first stage has led to contradictory results. On one hand, the regression outputs and the corresponding F-statistics led to the conclusion that the financial crisis has significantly impacted the ten variables that have been discussed above, on the other hand, the graphical analysis has put this outcome into question. While (5) *soc_assistance*, (6) *soc_housing*, (7) *unempl_rate*, and (10) *insolvency* were suggested to be the strongest affected in the statistical analysis, the graphical analysis only reached the same conclusion for (10) *insolvency*. For (5) *soc_assistance*, and (7) *unempl_rate*, the potential shock in 2005 appears to have influenced the regression outputs. Concerning the conclusion that (3) *u65_death*, and (8) *activity_rate* were the least affected by the shock, the statistical and graphical analyses are consistent.

5.1.3 The Relationship Between the Shock and the Environmental Indicators

Analogue to the scatterplots for the socio-economic variables, scatterplots have been drawn for the environmental variables (cf. Figure 5.2). The impact of the financial crisis that they show is relatively small. For (1) *ozone_conc*, the trend was slightly increasing between 2000 and 2007. A notable impact of the increasing trend has been the year 2003. An exceptionally long heatwave in the summer of 2003 has favoured the formation of ozone and as a consequence, has become an outlier year (Wilke, 2021). Omitting the year 2003, the trend appears stable. At the threshold, a downwards jump is visible, which is followed by a decreasing trendline. Furthermore, after the shock, the annual range is smaller with hardly any single outliers. (2) *No2_conc* has decreased relatively constant over the whole study period. Discontinuities at the threshold are negligibly small. In comparison to the other environmental variables, the observations spread over a larger range, and do so relatively evenly. Similarly, (3) *pm10_conc* has been decreasing over the whole period. The graph shows a noticeable downwards jump at the threshold and a slightly flatter post-shock trendline. In certain years, a few outliers can be identified. Overall, however, the distribution appears relatively even. Finally, (4) *water_use* shows a slightly increasing pre-shock and slightly decreasing post-shock trendline with a small downwards jump at the threshold. However, these impacts are marginal and cannot be assigned to the effect of the financial crisis with certainty.

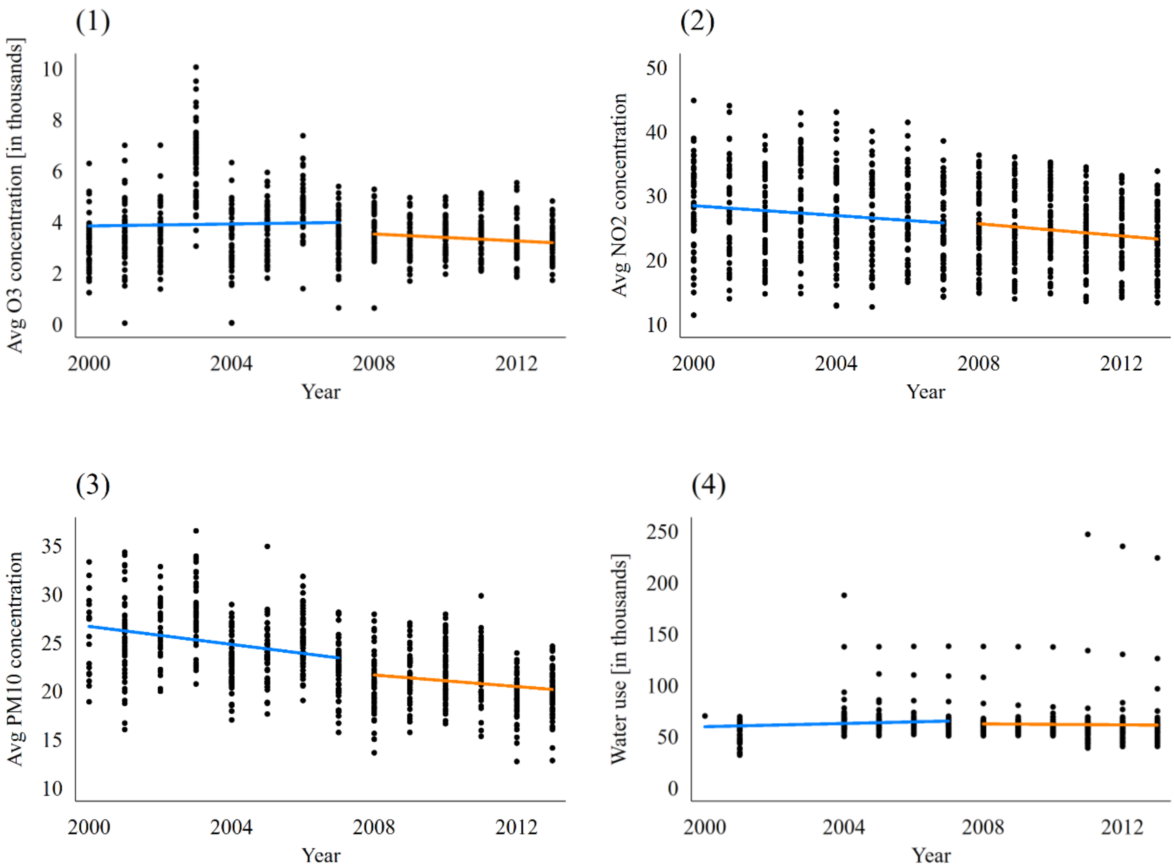


Figure 5.2: Linear trends of environmental indicators before and after the threshold.

Notes: (1)-(3) are reported in µg/m³ and (4) is reported in m³.

5.1.4 2SLS Estimation of the Causal Effect

The following section shows the second-stage estimates of the causal effect of the social and economic variables with a sufficiently large F-statistic on the four environmental variables. The estimates have been grouped into those with a relatively strong impact (*inf_mortality*, *u65_death*, *road_death*, and *insolvency)* and those with a relatively weak impact (*daycare*, *soc_assistance*, *soc_housing*, *unempl_rate*, *activity_rate*, and *companies)*. The categorization into weak and strong has been consistent over all four environmental variables.

The estimates of the variables with a relatively large causality of socio-environmental indicators on environmental indicators can be found in Table 5.4. First, the yearly infant mortality is expected to be positively associated with all environmental variables. An increase in infant mortality by one per 1000 persons is estimated to increase the accumulated ozone concentration above 70 µg/m³ by 68’395.1 µg/m³. The annual average concentration of NO2 is expected to increase by 532.5 µg/m³, and the annual average concentration of PM10 by 619.6 µg/m³. Total water use per 1000 persons is expected to increase by 669’955.8 m³. The estimate for *ozone_conc* is statistically significant at the 95% level, while those for *no2_conc* and *pm10_conc* are significant at the 99% level and the one for *water_use* is not significant.

Second, estimates suggest that *u65_death* positively impacts all of the environmental variables. Thereafter, an increase in total deaths of persons under 65 years by one per 1000 persons is associated with an increase in the accumulated ozone concentration above 70 µg/m³ of 2’046.6 µg/m³. The resulting increase in the annual average NO2 concentration is estimated to be 19.0 µg/m³ and the one of PM10 28.2 µg/m³. Water use is estimated to increase by 6’603.5 m³ per 1000 persons. As for the *inf_mortality*, the estimates are statistically significant at the 95% level for *ozone_conc*, the 99% level for *no2_conc* and *pm10_conc* and not significant for *water_use.*

Third, it is estimated that the number of deaths in road accidents has a positive impact on all environmental variables. More specifically, estimates suggest that an increase of 1 death in a road accident per 1000 persons increases the accumulated ozone concentration above 70 µg/m³ by 36’965.4 µg/m³. The annual average NO2 and PM10 concentrations are estimated to increase by 247.9 µg/m³ and 337.1 µg/m³ respectively. The total use of water is estimated to increase by 183’885.1 m³ per 1000 persons. The estimates for the first three variables are statistically significant at the 99% level, while the estimate of water_use is not significant.

Table 5.4: 2SLS Estimates of the Causal Effect of Social and Economic Variables on Environmental Variables, Variables with Stronger Effect.

	(1)	(2)	(3)	(4)
	ozone_conc	no2_conc	pm10_conc	water_use
inf_mortality	68’395.1**	532.542***	619.610***	669’955.8
	(33'388.0)	(197.479)	(197.867)	(480’729.8)
_cons	1’198.2	7.352	0.738	39’376.0**
	(1’108.1)	(6.693)	(6.804)	(16’513.5)
N	538	534	539	480
u65_death	2’046.6**	19.022***	28.233***	6’603.5
	(857.824)	(5.989)	(7.215)	(19’672.0)
_cons	-214.110	-8.536	-28.364**	49’938.7
	(1’543.8)	(10.744)	(12.927)	(34’743.3)
N	569	566	568	513
road_death	36’965.4***	247.924***	337.066***	183’885.1
	(10'016.0)	(78.821)	(62.882)	(202’642.0)
_cons	2’502.4***	18.737***	13.321***	57’247.4***
	(270.244)	(2.137)	(1.664)	(5’333.1)
N	563	561	580	531
insolvency	-970.515***	-4.316***	-8.162***	-2’081.9
	(197.767)	(0.868)	(1.199)	(4’340.5)
_cons	5’410.9***	33.609***	38.380***	65’711.8***
	(356.858)	(1.545)	(2.254)	(8’508.6)
N	657	674	629	484

Notes: Standard errors in parentheses, * p<0.10, ** p<0.05, *** p<0.01

Fourth, *insolvency* is estimated to negatively impact all environmental variables. More specifically, estimates suggest that an increase in the insolvency proceedings filed per 1000 people decreases the accumulated ozone concentration above 70 µg/m³ by 970.5 µg/m³. The annual average NO2 and PM10 concentrations are estimated to increase by 4.3 µg/m³ and 8.2 µg/m³ respectively. Total use of water is estimated to decrease by 2’081.9 m³ per 1000 persons. The estimates for the first three variables are statistically significant at the 99% level, while the estimate for water_use is not significant.

A pattern that emerges over all four variables is that the estimates for *ozone_conc* and *water_use* are relatively large, while the estimates for *no2_conc* and *pm10_conc* are relatively small. Furthermore, the estimates for *water_use* are never significant, whereas those for the remaining three variables are all significant at the 95% and 99% levels.

Table 5.5: 2SLS Estimates of the Causal Effect of Social and Economic Variables on Environmental Variables, Variables with Weaker Effect.

	(1) **ozone_conc**	(2) **no2_conc**	(3) **pm10_conc**	(4) **water_use**
daycare	-142.056***	-0.937***	-1.305***	-239.531
	(45.847)	(0.205)	(0.206)	(615.202)
_cons	6’347.5***	44.621***	48.713***	66’397.3***
	(924.784)	(4.180)	(4.163)	(12’076.6)
N	577	576	574	503
soc_assistance	24.745***	0.111***	0.189***	56.132
	(4.674)	(0.021)	(0.016)	(115.569)
_cons	3’246.4***	24.039***	20.167***	61’038.3***
	(98.707)	(0.460)	(0.316)	(1’563.0)
N	657	674	629	484
soc_housing	27.197**	0.191***	0.234***	255.534**
	(10.724)	(0.057)	(0.045)	(104.957)
_cons	2’559.9***	18.951***	14.160***	51’216.8***
	(382.392)	(2.029)	(1.611)	(4’001.8)
N	379	375	386	353
unempl_rate	92.077***	0.634***	0.800***	492.965
	(25.289)	(0.173)	(0.088)	(533.045)
_cons	2’586.1***	19.199***	14.241***	57’496.7***
	(252.365)	(1.734)	(0.887)	(4’967.1)
N	582	583	594	531
activity_rate	-296.485***	-2.080***	-2.908***	-1’289.7
	(109.417)	(0.657)	(0.742)	(1’373.3)
_cons	20’275.4***	143.491***	187.136***	134’908.1*
	(6’196.0)	(37.277)	(42.090)	(77’610.5)
N	581	582	593	531
companies	-61.578***	-0.409***	-0.570***	-324.488
	(20.791)	(0.127)	(0.124)	(343.812)
_cons	5’866.3***	41.289***	44.220***	74’924.03***
	(809.734)	(4.883)	(4.788)	(13’669.1)
N	565	568	577	526

Notes: Standard errors in parentheses, * p<0.10, ** p<0.05, *** p<0.01

Table 5.5 presents the estimates of the variables with a weaker estimated causal effect on the environmental variables. As for the previous four variables, estimates are significant at least at the 95% level for *ozone_conc, no2_conc*, and *pm10_conc*, but mostly insignificant for *water_use*. Not only the levels of significance resemble those reported in Table 5.4, but also the magnitudes of the estimate. The pattern of large estimates for *ozone_conc* and *water_use* and small estimates for *no2_conc* and *pm10_conc* persists for the estimates in Table 5.5. Overall, estimates for *companies*, *soc_housing*, and *soc_assistance* are relatively small, whereas those for the remaining three variables are slightly larger.

5.2 Discussion

Estimates of ten socio-economic indicators confirm the hypothesis that there is a significant impact of the social and economic dimensions of sustainability on environmental sustainability in German cities. This indicates that changes in either social or economic sustainability do not translate into equal changes in overall sustainability. Instead, they also impact environmental sustainability, which increases or decreases the impact on overall sustainability. This section first discusses the first-stage and thereafter the second-stage regressions.

5.2.1 First-stage Regressions

The first-stage regressions were performed to get an indication of the strengths of the shock on the explanatory variables and to ensure that the F-statistics are large enough to respect the first of the four IV conditions. However, A large share of the socio-economic variables did not fulfil the required condition to report unbiased estimates through the shock-based IV method. The comparison of the descriptive statistics (cf. Table 5.1) and the scatterplots (cf. Figures 5.1 and C.1) suggest that missing data had a major influence. For the indicators with a weak first-stage regression, more missing observations are reported. The scatterplots show that often whole years are without any observations. In addition, many of the scatterplots for variables with a low F-statistic suggest a misspecification or absence of the shock. Furthermore, the category of the indicators seems to play a role. Most of the indicators that did not qualify for the 2SLS regression are related to transportation, housing or culture. This suggests that those areas may have been too little affected by the financial crisis to legitimate it a shock that leads to a regression discontinuity.

Among the indicators with a strong first stage, the largest estimates with respect to the variables mean have been reported for *insolvency*, *unempl_rate*, and *soc_housing*. On the opposite side, the smallest estimates have been reported for *activity_rate* and *u65_death*. This is consistent with the intuition that the former three variables are heavily dependent on external conditions to perform better, while the latter two are more consistent indicators that fluctuate less in a short term view.

5.2.2 Second-stage Regression

Overall, the expectation for the second-stage regressions was that there is a positive causal relationship between two constraint indicators, while there is a negative relationship between a maximisation and a constraint indicator (cf. Table C.1 in Appendix C). The logical reasoning behind this is that, when a higher value in the socio-economic indicator improves socio-economic sustainability, this should improve environmental sustainability. All environmental indicators in this study are constraint indicators, where smaller values are more sustainable. Therefore, the expected relationship between a maximisation socio-economic indicator and an environmental indicator is negative and the one between a constraint socio-economic indicator and environmental indicator is positive. Out of the ten regressions, seven correspond to these expectations. The three variables for which the estimates contradict the expectations are *soc_assistance*, *soc_housing,* and *insolvency*. The first two might be misspecified as maximisation indicators. They were qualified as maximisation indicators because it was considered that socially sustainable cities offer more social support to their people. Therefore, higher values in *soc_assistance* and *soc_housing* were considered an improvement in social sustainability. However, the alternative reasoning is that higher numbers in *soc_assistance* and *soc_housing* indicate that people are worse off. As a consequence, numbers should not exceed a certain threshold, which categorizes the variables as constraint variables. To determine whether a mis-categorization lies at the bottom of this, the changes in the cities would need to be analyzed in more detail, which exceeds the scope of this study. The third exception is *insolvency*, where more insolvency proceedings filed decrease economic sustainability, but increase environmental sustainability. A possible explanation for this relationship could be that insolvent businesses are more environmentally unsustainable. Having them go out of business would improve the conditions for the environment. However, as the Regionaldatenbank Deutschland does not supply any information on the kinds of businesses that file insolvency proceedings, it is not possible to confirm or deny this hypothesis.

The estimated magnitude of the causality varies strongly between the different socio-economic indicators. Depending on the variable, a change of one unit can be a more or less important change. To compare all variables, the 2SLS estimates have been divided by the variables' means, which were reported in Table 3.1. Illustrations of the estimates' magnitudes are shown in Figure 5.3 for the variables with a stronger causal effect and in Figure 5.4 for those with a weaker causal effect. Thereafter, the strongest causal effects on environmental indicators come from *inf_mortality, road_death, u65_death,* and *insolvency*. At first sight, this may be surprising. Remembering the first-stage regressions, only *insolvency* was among the ones with a large F-statistic. Considering the scatterplots (cf. Figure 5.1), all four have not been the ones with the greatest change in trendlines after the shock. There are two possible explanations for this divergence. First, for many variables with a weaker estimated causal effect, there was the suspicion of a shock misspecification. This possible misspecification might have been picked up and eliminated by the 2SLS regression. Hence, variables with a correctly specified shock would show stronger causal effects. Second, changes in environmental indicators have not occurred as a consequence of changes in socio-economic indicators. In other words, there is no strong causal relationship between the variables heavily affected by the shock and the environmental variables. A good example of this possibility is *companies.* The scatterplot did not suggest a shock misspecification but suggested the strongest impact of the shock on all of the variables. The relatively low estimates for *companies* indicate that this impact has not been translated into the environmental indicators.

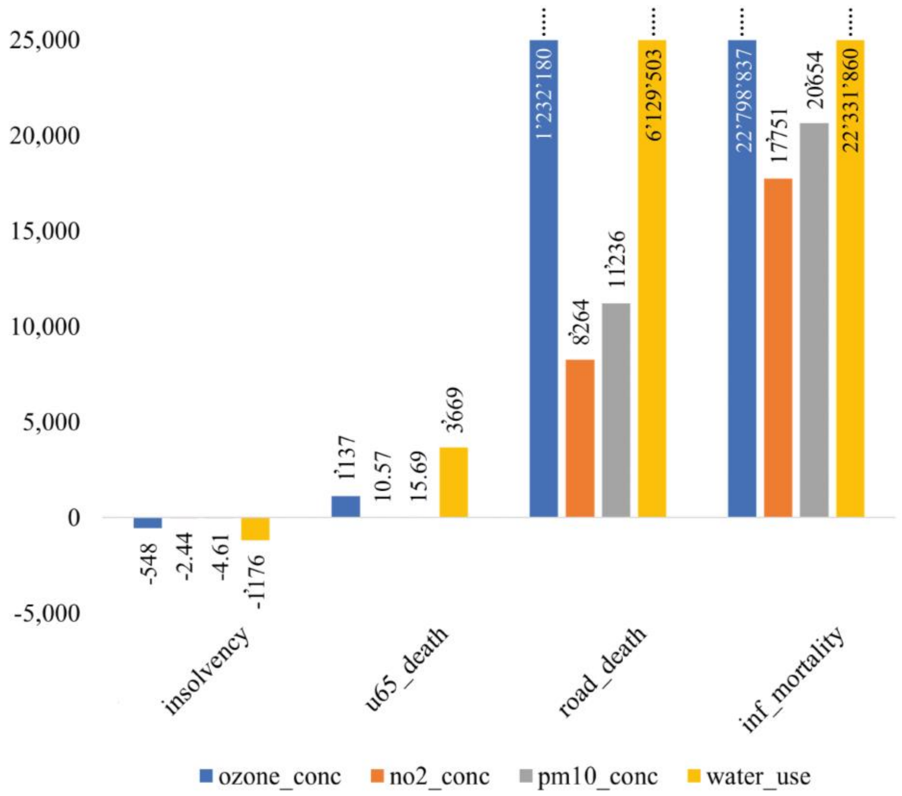


Figure 5.3: Illustration of the Magnitude of the Estimated Causal Effect, Variables with Stronger Effect.

Notes: Certain values were too big to fit into this illustration. Corresponding estimates are indicated with '…..' at the top of the bars. Units correspond to variable units (cf. Table 3.1).

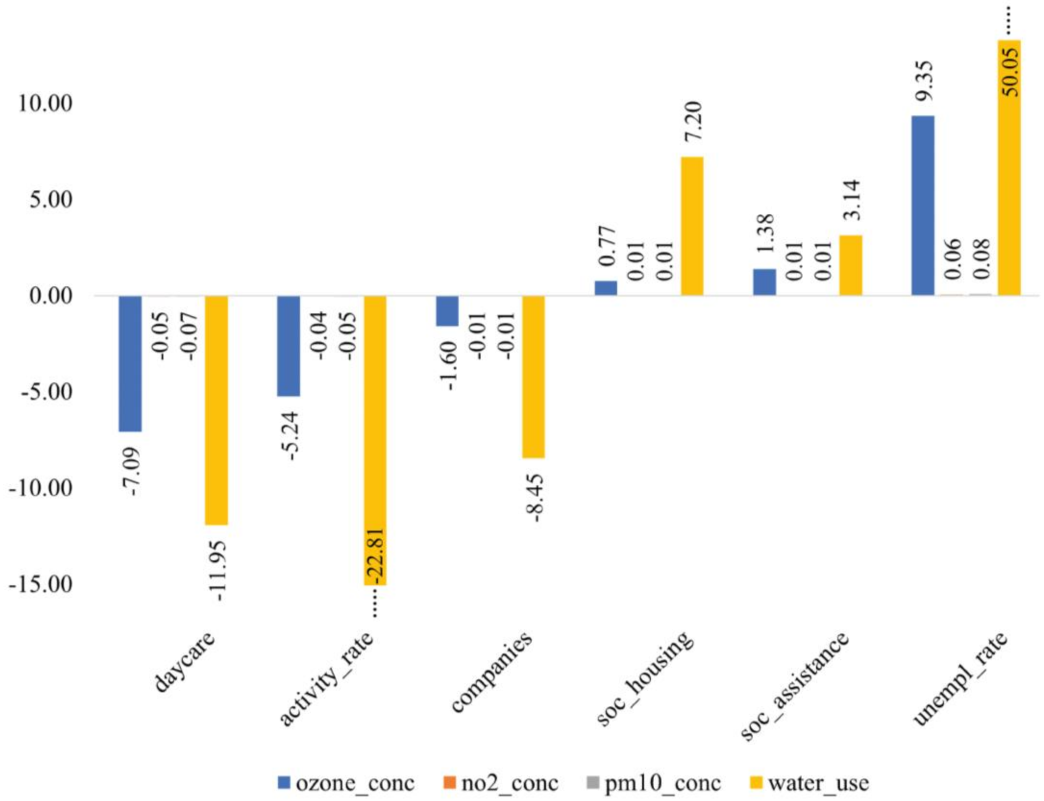


Figure 5.4: Illustration of the Magnitude of the Estimated Causal Effect, Variables with Weaker Effect.

Notes: The estimate of *unempl_rate* on *water_use* fit into this illustration. The corresponding estimates are indicated with '…..' at the top of the bars. Units correspond to variable units (cf. Table 3.1).

When discussing the descriptive statistics (cf. Section 5.1.1), the question was asked whether a smaller amount of observations leads to less significant estimates. The variables with the least observations are *soc_housing*, *inf_mortality*, and *water_use*. No differences in significance were observable for the first-stage regressions. In the second-stage regressions, estimates for *water_use* were strongly less significant. Likely, this is at least partially caused by the relatively large number of missing observations. For *soc_housing and inf_mortality*, the differences are smaller, but estimates of these two variables are also slightly less significant. As this difference is relatively small, it is uncertain whether it can be attributed to the fewer observations.

When comparing the causality between different pillars, one surprising aspect of this insight is that the majority of the economic indicators are not among the most affected indicators, although the shock was of economic nature. The first stage estimates, relative to the indicators' mean, suggest a slightly stronger effect of the shock on economic indicators. Thereafter, the 2SLS results suggest that the causality between social and environmental sustainability is stronger than the one between economic and environmental sustainability. These findings are similar to those made in previous studies. The causal effect that Svensson et al. (2018) have found from social on environmental sustainability can be confirmed. In addition, the fact that Svensson et al. (2018), as well as Mirshojaeian Hosseini and Kaneko (2012), have not found a causal relationship between environmental and economic sustainability can be an indicator why the effect of this study was smaller than the one between social and environmental sustainability. However, contrary to the findings of the previously named authors, this study has found a statistically significant causal effect of economic on environmental sustainability.

Among the environmental indicators, it is noticeable that the impact is significantly weaker for *water_use* in nine out of ten cases. This observation is coherent with the impression obtained from Figure 5.2, where hardly any change between pre- and post-crisis trendlines was observable. Of the remaining three variabels, the impact tends to be the strongest for *pm10_conc*, followed by *ozone_conc* and then *no2_conc*. These observations as well correspond to the impressions obtained from the illustrations in Figure 5.2, where *pm10_conc* and *ozone_conc* showed a larger jump and change in slope of the trendlines than *no2_conc* did. It is noticeable that this order is consistent with the order of the variables' standard deviations and their estimates’ standard errors. *Water_use*, the variable with the weakest estimates, is at the same time the variable with the highest standard deviation and the one with the largest standard errors. This indicates that the conclusion about a causal relationship is the weakest for *water_use.* For *pm10_conc*, on the opposite, they are the strongest, while for *ozone_conc* and *no2_conc,* they are in between. Another noticeable pattern among the environmental variables is that for all ten socio-economic variables, estimates were considerably larger for *ozone_conc* and *water_use* than for *no2_conc* and *pm10_conc.* While it can be argued that those for *water_use* the estimates might not be as accurate, the strong difference persists between the remaining three variables, for which the estimates are expected to be more accurate. The reason for this difference is not known at this point. On the contrary, it is rather surprising because nitrogen oxides, one of which is NO_2, are among the precursor substances of ozone (Hendriks, Forsell, Kiesewetter, Schaap & Schöpp, 2016). As a consequence, it would be expected that they react similarly to a change in socio-economic variables. For a more in-depth understanding of the pronounced differences between the estimates reported, further scientific investigations are necessary.

5.3 Limitations

There are several limitations to the present study. Hereafter, the following limitations are discussed: the limitations of the model construction, the unavailability of data, the size and construction of the city sample, and a possible misspecification of the shock. This list of limitations is not necessarily exhaustive. However, those limitations are considered to be the ones that most severely threaten the validity of the estimated results.

5.3.1 Model Construction

The instrumentation of all explanatory variables with the shock of the financial crisis has led to the need for separate equations for each of the explanatory variables. The reason for this is that one instrument cannot be used multiple times in the same 2SLS regression. This translates into a probable violation of the independence assumption (cf. Section 4.2.1) and the estimates are likely to remain biased. While it is expected that they are no longer affected by simultaneity, they are biased by omitted variables because the environmental variables are not fully explained by one single socio-economic variable but depend on several of them. This is also likely to be the reason why certain estimates reported extremely high or low coefficients. The chosen approach was deemed to be the most suitable for this study. However, further investigations into a more appropriate method can improve future studies in this area.

5.3.2 Data Availability

Another important limitation is the unavailability of data at the city level. This issue has already been discussed by numerous authors (see for example: Gibberd, 2017; Kawakubo et al., 2018; Phillis, Kouikoglou & Verdugo, 2017). A consequence of this limitation is that this study only considers German cities. Whether results are valid for other locations requires further studies. In addition, the choice of indicators has largely been influenced by what indicators are available, and not by what indicators best fit the research question analysed. For example, the environmental indicator that Rockström et al. (2009) use for the planetary boundary of climate change and that is highly prominent in sustainability discussions is CO_2 emissions. Efforts were made to find data on German cities' CO_2 emissions, yet, they were not successful. They have either not been made publicly available or not been collected at all. The same is true for many more indicators. This also had the consequence that the Doughnut model had not only been adapted in ways that make it more representative for the city case, but also according to what variables were available. Especially the environmental indicators are a one-sided representation of environmental sustainability. Three out of four variables are connected to air quality and the fourth variable only provided weak results. A more comprehensive application of the Doughnut would also have allowed to compare causal relationships between the most unsustainable and sustainable dimensions and see whether performance impacts their relationship. However, for this not only data was missing but also specific thresholds have not been defined yet for many variables.

It is a weakness of this study that numerous interesting and crucial dimensions of sustainability had to be omitted. To study causal relations between different dimensions of sustainability and improve them simultaneously, abundant and high-quality data that is easily accessible is key. Cities are urged to carefully collect data for diverse indicators and cooperate to make them easily accessible to the public.

5.3.3 Sample Selection

Closely related to the issue of unavailable data is the relatively small city sample used in this study. The sample used in this study is entirely coherent with the list of cities for which sufficient amounts of data in the variables studied are available. As previously discussed, 2800 settlements in Germany qualify as cities according to the BBSR. Krejcie and Morgan (1970) have specified a widely used formula for determining the necessary sample size to be representative of a given population. According to this formula, a sample of 338 cities would be necessary for a population of 2800 cities. With this sample size, the margin of error is 5 percent. This study's sample of 60 individuals is not entirely unqualified to represent a population of 2800, however, the associated margin of error lies at approximately 12 percent.

Furthermore, it is not only the small sample that threatens the representativeness of the study, but also the individual cities that are part of the sample. As discussed in Section 3.4, small cities are disregarded in this sample. Furthermore, the remaining cities are not equally represented. The distribution of cities according to their sizes in the German population and the study sample is shown in Figure 5.3. Thereafter, the cities with 50'000 to 99'000 inhabitants are underrepresented, while cities with more than 100'000 inhabitants are overrepresented. It is expected that this is because larger cities have more means and incentives to measure and report a wide variety of data. As a consequence, this misrepresentation is hard to avoid and would exceed the scope of this study.

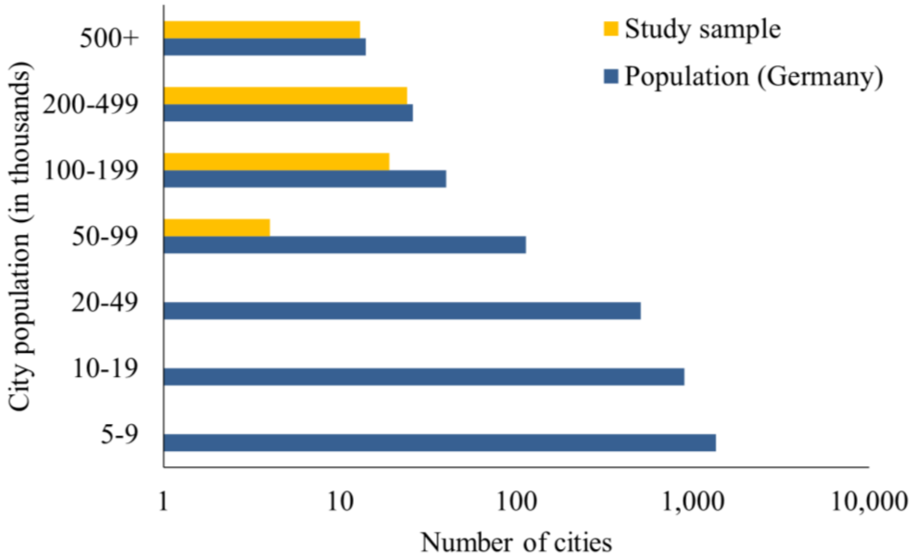


Figure 5.5: Comparison of City Sizes in Germany and the Study Sample.

Notes: The comparison of sample and population is slightly distorted. City sizes of the population are reported for the year 2020 (Data: Statistisches Bundesamt, 2020), and city sizes of the sample are reported for the year 2013 (Data: Eurostat, 2022).

5.3.4 Shock Misspecification

There is the possibility that the moment of the shock has not been optimally specified. This possibility should be investigated by future studies as a better fitting shock would lead to more accurate and holistically valid results. This study has briefly considered two alternative thresholds. First, it takes some time for a shock to affect other variables to a degree that is noticeable in the respective data. The financial crisis started in late 2007, however, it was not until 2008 that it turned into the most severe crisis since the Great Depression (Ötker-Robe &

Podpiera, 2013). This study has followed evidence by Ötker-Robe and Podpiera (2013), which shows that data on European countries changed significantly in the year 2008. However, if the impact on socio-economic indicators took longer in the studied sample of German cities, a threshold between 2008 and 2009 would be more appropriate. The first- and second-stage regressions of this later shock have been performed and the new estimates of the causal effect are reported in Table 5.6. The F-statistics in the first-stage regressions have changed and therefore, so did the selection of variables suitable for IV estimation. *Inf_mortality* has dropped out, while *living_area* has been added to the list of instrumented variables. However, the levels of significance of the estimates of *living_area* are relatively weak. The only other change in significance levels can be observed for *soc_housing*, where now the estimates are statistically significant for all 4 environmental variables. For all persisting variables, positive impacts have stayed positive and negative have stayed negative. The strength of the shock however has become stronger for some and weaker for other variables. What is noticeable is that in a majority of cases, *ozone_conc* and *water_use* have been similarly affected and *no2_conc* and *pm10_conc* have been similarly affected. On average, there has been an increase in standard errors over all variables. In conclusion, the change of threshold has improved the level of significance and decreased standard errors in certain cases. Overall, however, it does not appear to be a better fitting threshold. All the same, the analysis of this alternative threshold remains useful as it confirms the positive and negative relationships found in the initial regressions.

Table 5.6: 2SLS Coefficient Estimates Using 2008-2009 as the Threshold.

	ozone_conc	no2_conc	pm10_conc	water_use
daycare	-143.661***	-0.742***	-0.854***	-296.022
	(39.693)	(0.171)	(0.133)	(510.355)
u65_death	3’051.4**	20.969***	24.784***	13’746.4
	(1’237.5)	(7.618)	(7.323)	(25’182.1)
road_death	46’332.8***	245.566***	269.894***	228'072.0
	(11'540.0)	(83.785)	(56.024)	(226'412.0)
soc_assistance	29.398***	0.119***	0.181***	71.331
	(5.580)	(0.025)	(0.019)	(139.297)
soc_housing	38.471***	0.174***	0.187***	310.824***
	(13.392)	(0.061)	(0.043)	(117.076)
unempl_rate	110.169***	0.606***	0.635***	584.112
	(26.726)	(0.177)	(0.083)	(564.831)
activity_rate	-339.009***	-1.918***	-2.201***	-1’354.7
	(114.137)	(0.627)	(0.577)	(1’290.6)
companies	-40.152***	-0.210***	-0.219***	-187.063
	(10.109)	(0.060)	(0.035)	(178.216)
insolvency	-1’080.0***	-4.360***	-7.350***	-2’301.9
	(223.580)	(0.948)	(1.222)	(4’557.1)
living_area[1]	-227.046**	-0.802	-1.134***	-1’071.9
	(101.073)	(0.662)	(0.419)	(1’298.9)

Notes: Standard errors in parentheses, * p<0.10, ** p<0.05, *** p<0.01. [1]The F-statistic of this was not above 10 in the initial regression.

Table 5.7: 2SLS Coefficient Estimates Using 2004-2005 as the Threshold.

	ozone_conc	no2_conc	pm10_conc	water_use
daycare[1]	-999.157	-45.283	5.378	-4’641.5*
	(3’619.7)	(313.041)	(4.360)	(2’766.5)
inf_mortality	-46’508.9***	414.884***	287.799***	62’693.9
	(17’284.3)	(142.701)	(110.751)	(567’220.0)
u65_death	-949.311***	11.058***	10.040***	-19’535.5**
	(352.395)	(2.703)	(1.772)	(9’776.8)
road_death	-30’384.9	425.064**	345.382***	-254’379.0
	(23'894.0)	(201.825)	(122.209)	(351’715.0)
soc_assistance	10.880***	0.070***	0.103***	-41.647
	(2.814)	(0.013)	(0.008)	(57.537)
soc_housing	-9.267	0.235***	0.176***	-313.034**
	(9.685)	(0.070)	(0.048)	(158.421)
unempl_rate[1]	-96.290	1.729**	1.324***	-951.745
	(82.248)	(0.775)	(0.354)	(1’322.6)
activity_rate	113.786	-1.879***	-1.893***	1’356.3
	(81.637)	(0.646)	(0.586)	(1’948.3)
companies	10.533	-0.170***	-0.160***	122.943
	(7.770)	(0.051)	(0.029)	(164.852)
insolvency	-408.124***	-2.613***	-4.352***	2’061.8
	(105.840)	(0.502)	(0.458)	(2’827.5)
car_journey[2]	-44.379**	0.392***	0.454***	-1’031.6**
	(17.381)	(0.104)	(0.107)	(432.284)
carmcycle_	-24.257	0.338***	0.358***	-1’075.3**
journey[2]	(17.251)	(0.104)	(0.086)	(459.181)
bicycle_	72.594**	-0.761***	-0.784***	1’562.2**
journey[2]	(33.920)	(0.178)	(0.197)	(671.003)
theatre[2]	96’003.2***	456.934***	483.482***	-390’004.4**
	(19’513.3)	(103.459)	(75.825)	(186834.0)

Notes: Standard errors in parentheses, * p<0.10, ** p<0.05, *** p<0.01. [1]The F-statistic of these variables is no longer above 10. [2]The F-statistic of these was not above 10 in the initial regression.

Second, the examination of the scatterplots in Figure 5.1 suggested a shock in 2005. Therefore, the first- and second-stage regressions have also been performed with this earlier threshold. Corresponding estimates are reported in Table 5.7. While a discontinuity in that moment has been conspicuous, it also needs to be noted that larger gaps of missing observations have occurred between 2000 and 2004. As the new pre-shock period is already short itself, several years with no observations considerably limit the insights that can be gained from the analysis. One suggestion from the new regression output that goes against the expectations and the conclusions from the initial regressions is the inverse impact that has occurred especially frequently for *water_use* and occasionally for *ozone_conc*. The origin of this change is unknown at this point and would require further information and deeper analyses. For *u65_death*, *soci_assistance*, and *insolvency*, the variables with fewer missing observations and that were already included in the initial regressions, the estimated impacts of the shock are overall smaller. At the same time, the associated standard errors are also smaller. Considering that the degrees of significance remain largely unchanged, those estimates might be more accurate than those of the initial regressions. However, it needs to be remembered that this brief analysis of the earlier shock has not studied the conditions that are necessary for unbiased IV estimates. For this reason, it is suggested that this topic is covered in future research.

6 Conclusion

The research question of this study was *what is the causal effect of socio-economic sustainability on environmental sustainability in cities?* To answer this question, this study has quantified the causal effect of social and economic sustainability on environmental sustainability in the city context. As OLS estimates were expected to be biased by simultaneity, the estimation of the causal effect occurred through the application of the shock-based IV method. The shock of the financial crisis of 2007 was used as the instrument that isolates the causality from socio-economic to environmental sustainability from the causality in the inverse direction. The obtained estimates were to a large part statistically significant and provide evidence that in German cities, there is a causality from social to environmental sustainability, as well as from economic to environmental sustainability. More specifically, most estimates suggest a positive relationship between a constraint socio-economic indicator and environmental indicators, and a negative relationship between a maximization socio-economic indicator and environmental indicators. This corresponds to the expectation that an improvement in socio-economic sustainability leads to an improvement in environmental sustainability.

6.1 Research Aims

By providing statistically significant evidence of the causal effects of socio-economic to environmental sustainability, this study has reached the aim of adding to a better understanding of the interrelationships between the different pillars of sustainability. To date, the little amount of understanding that exists on these relationships is a large gap in literature.

A further aim of this study has been to contribute to a more uniform approach to the topic of city sustainability. The heterogeneity that exists in the field is a persistent gap in literature, as it impedes the combined development of previous research findings. While creating a more homogenous field of study takes time and numerous studies, this study has put forward the approach that is considered to best fit the topic and has thereby made one small step in this direction.

Some limitations hindered the entire attainment of the study's aims. Due to data unavailability and the suggested strong dependence of results on study location characteristics, this study has been limited to the analysis of 60 German cities. As a consequence, the representativeness of the outcomes is likely to be limited to medium and large cities in Germany. Missing data and gaps in the literature have further limited the application of the Doughnut model. While it was possible to use it as a graphical representation of the context the study belongs in, it was not possible to determine which planetary boundaries were transgressed and which socio-economic foundations were not met by the cities in the study sample.

6.2 Practical Implications

Overall, these results support the argument for the necessity of a holistic approach to city sustainability. The findings of this study are of great relevance to a series of actors. First, researchers should consider the existent causalities within sustainability in their studies to truly understand city sustainability. Second, decision- and policy-makers are required to account for the causalities when they make decisions or plan projects. Only then, their actions can target what they aim for. Third, actors that rank cities through their indicators need to include causalities in their assessment to better report cities' sustainability performances.

A further practical implication for public organizations at the city level is their responsibility to collect data. Data collection needs to cover a wide range of indicators and it must be conducted regularly. It is only when high-quality data is available that estimates can truthfully reflect the real world and the nature of the causalities can be understood.

6.3 Future Research

There have been a series of limitations to this study. As a consequence, there are several suggestions for future research. First, it is proposed to conduct the same research at different regional levels. Germany has been the preferred location for the present study due to the relatively high quality and coverage of data. However, to truly understand the causal relationship between socio-economic and environmental sustainability, the relationship should be tested in different environments.

Second, different channels of causality should be investigated. For example, as discussed in Section 4.2., it is expected that the causality not only goes from socio-economic indicators to environmental indicators but also the other way around. Similarly, there may be interesting causal relationships between social and economic sustainability or further pillars of sustainability that have not been touched upon in this study. Quantifying these causal relationships would offer valuable insights into the interplays between different pillars of sustainability and should be taken on by future research.

Third, if more means are available to other researchers, they should invest in accessing higher quality data. On one side, the duration of the studied period should be increased to avoid single events biassing the outcome. On the other side, the choice of indicators should be diversified, especially for the environmental indicators. In the present study, the choice was strongly one-sided and overrepresented air quality. A larger selection of indicators would further allow making more differentiated conclusions about causalities. For example, it can be studied whether causalities differ when the dimensions operate within the safe and just space for humanity of the Doughnut model, versus when they do not.

Fourth, for the German case, the shock of the introduction of the Agenda 2010, or other alternative shocks, should be investigated. The brief consideration of the shock in 2005 suggests that interesting and complementary results to those in this study might be generated. Thereby, this study’s results could be confirmed or contested with a suggestion of a more suitable causal relationship.

By intensifying future research on the topic of city sustainability, cities are given the grounds to respect their responsibilities as important actors in overcoming the current sustainability challenges. In an active discourse, a consensus on efficient and effective practices can be attained, that transform cities into spaces that conserve the environment, that are just to their people, and that allow the economy to flourish.

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Appendix A: Previous Research and Theoretical Framework

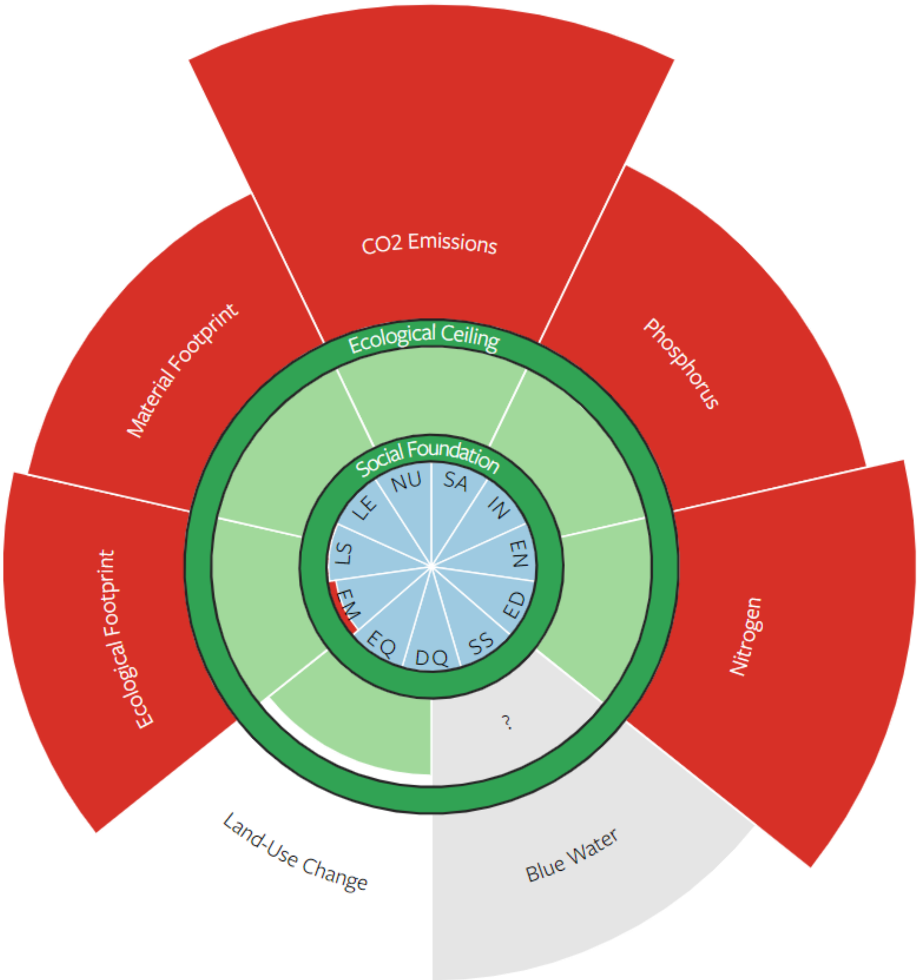


Figure A.1: Doughnut model for Germany, 2007. Source: Fanning et al. (2022).

Notes: LS=life satisfaction, LE=life expectancy, NU=nutrition, SA=sanitation, IN=income poverty, EN=access to energy, ED=secondary education, SS=social support, DQ=democratic quality, EQ=equality, EM=employment.

Appendix B: Data

Table B.1: List of Cities in the Study Sample.

Aachen	Erfurt	Kiel	Osnabrück
Augsburg	Erlangen	Krefeld	Pforzheim
Berlin	Essen	Köln	Potsdam
Bielefeld	Frankfurt (Oder)	Leipzig	Reutlingen
Bonn	Frankfurt am Main	Leverkusen	Rostock
Braunschweig	Freiburg i.B.	Ludwigshafen	Saarbrücken
Bremen	Gelsenkirchen	Lübeck	Solingen
Bremerhaven	Gera	Magdeburg	Stuttgart
Chemnitz	Göttingen	Mainz	Trier
Cottbus	Halle (Saale)	Mannheim	Ulm
Darmstadt	Hamburg	Mönchengladbach	Weimar
Dortmund	Hannover	Mülheim a.d.Ruhr	Wiesbaden
Dresden	Ingolstadt	München	Wolfsburg
Duisburg	Jena	Münster	Wuppertal
Düsseldorf	Karlsruhe	Nürnberg	Würzburg

Figure B.1: Adaptation of the Doughnut Used in this Study (authors illustration, inspired by Raworth, 2017, p. 50).

Appendix C: Empirical Analysis

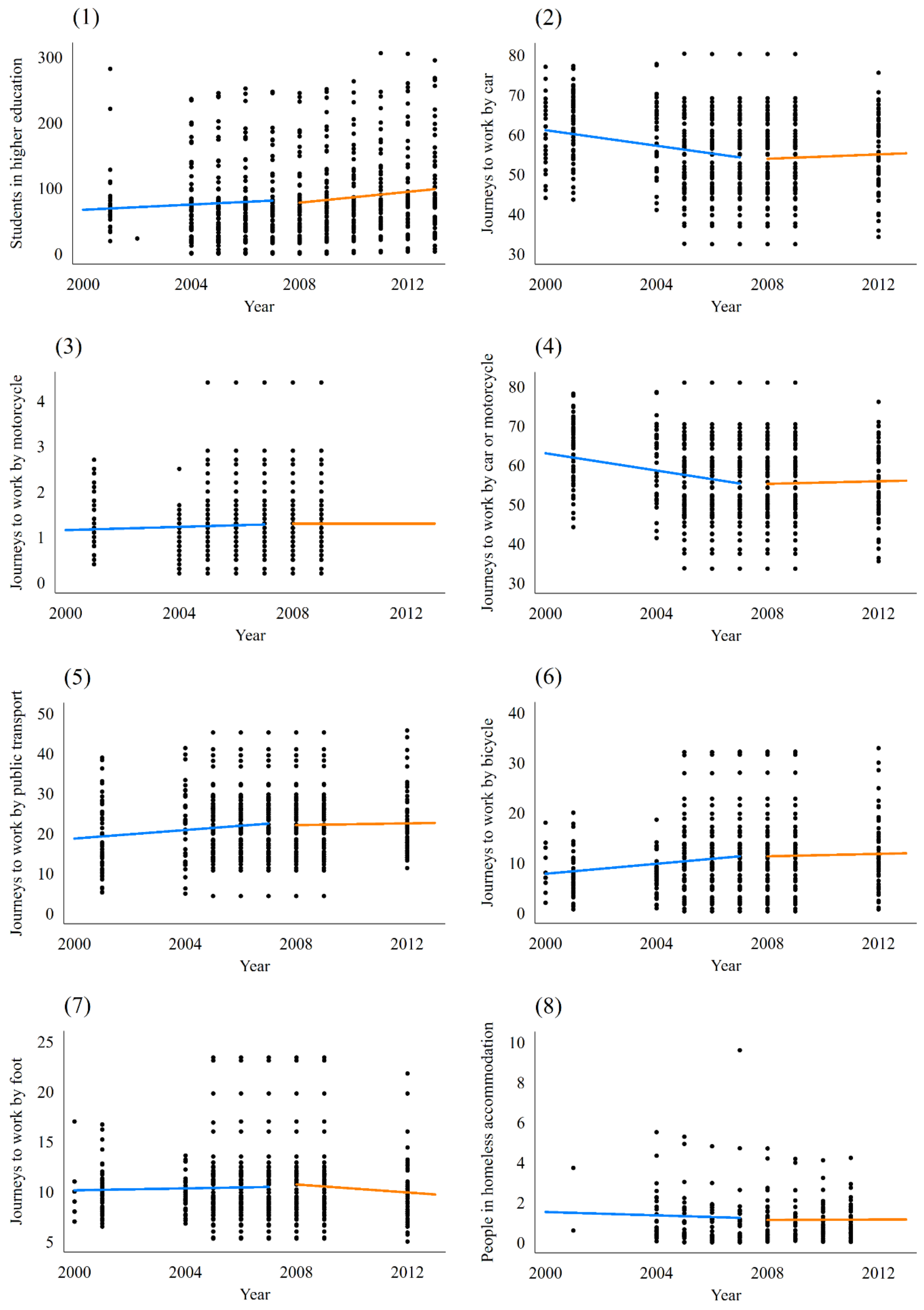
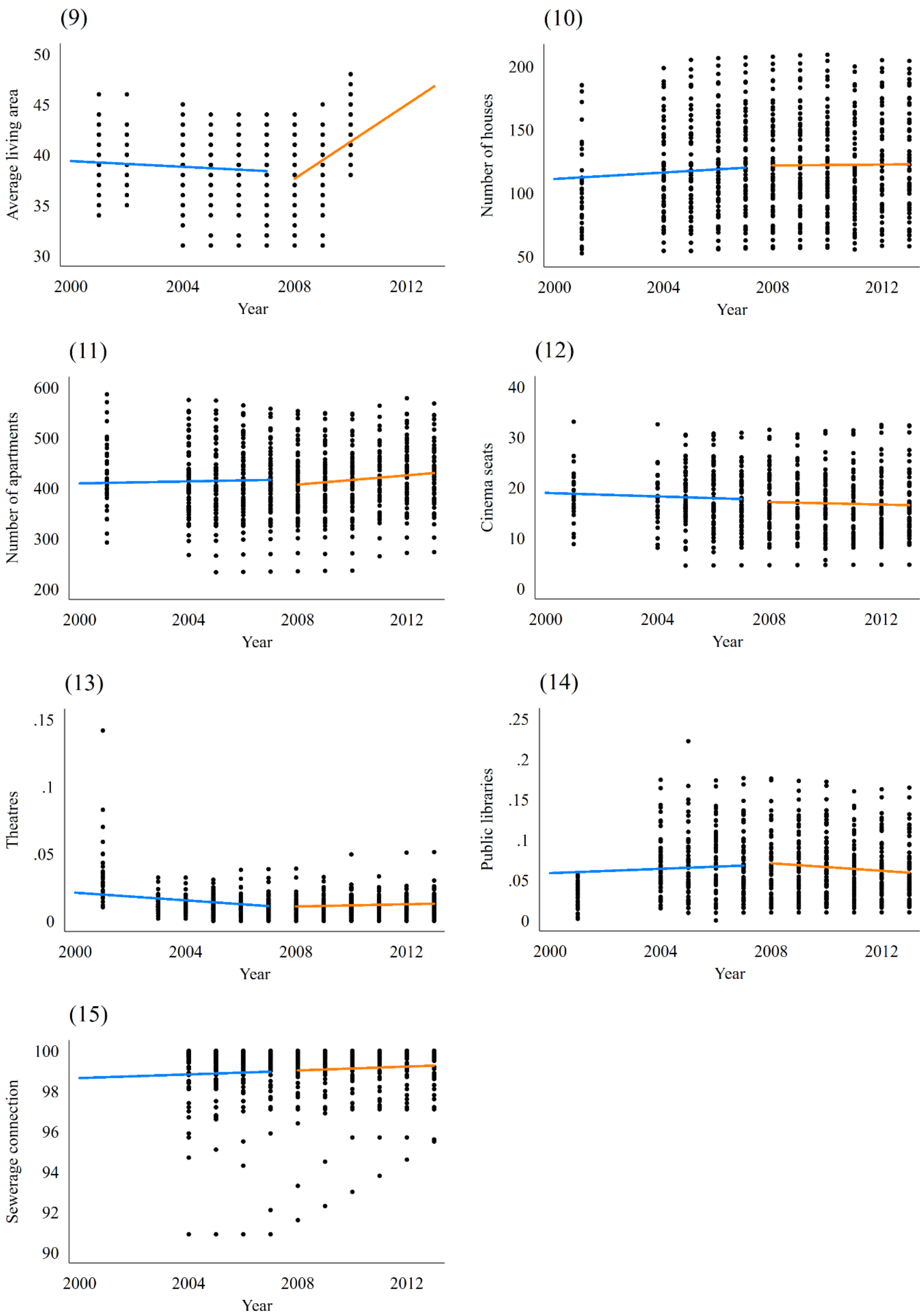


Figure C.1: Scatterplots for remaining variables with linear pre- and post-shock trendline, 2000-2013.



Continuation of Figure C.1: Scatterplots for remaining variables with linear pre- and post-shock trendline, 2000-2013.

Notes: (1), (8) and (10)-(14) are reported in the number per 1000 persons of the total population, (2)-(7) and (15) as percentages and (9) in m^2.

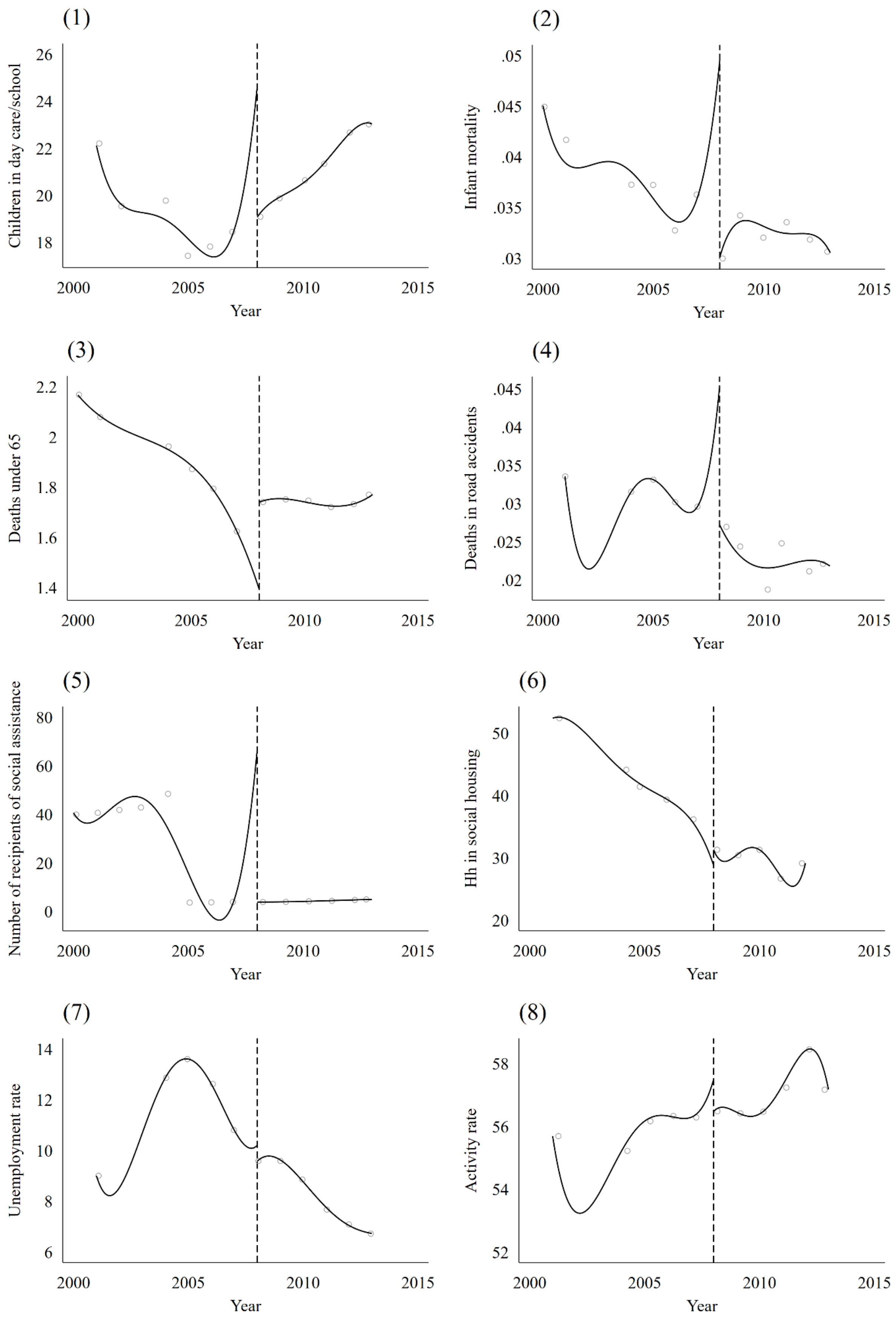
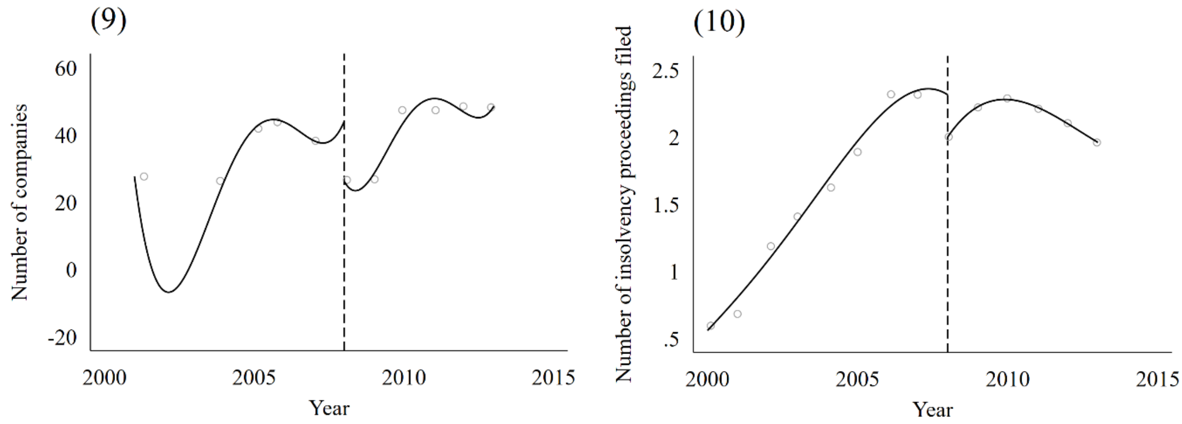


Figure C.2: Scatterplots for (1) daycare, (2) inf_mortality, (3) u65_death, (4) road_death, (5) soc_assistance, (6) soc_housing, (7) unempl_rate, (8) activity_rate, (9) companies and (10) insolvency, with fourth order polynomial pre- and post-shock trendline, 2000-2013.



Continuation of Figure C.2: Scatterplots for (1) daycare, (2) inf_mortality, (3) u65_death, (4) road_death, (5) soc_assistance, (6) soc_housing, (7) unempl_rate, (8) activity_rate, (9) companies and (10) insolvency, with fourth order polynomial pre- and post-shock trendline, 2000-2013.

Table C.1: Overview of the Algebraic Signs Necessary for an Improvement of Sustainability for Different Combinations of Constraint and Maximization Indicators.

		Explained variable	
		Constraint indicator	**Maximization indicator**
Explanatory variable	**Constraint indicator** (lower value improves sustainability)	positive estimate	negative estimate
	Maximization indicator (higher value improves sustainability)	negative estimate	positive estimate